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CONTINUOUS-WAVE THREE-COMPONENT SONIC ANEMOMETER

H. L. Fox

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
Bedford, Massachusetts 01730

Contract Monitor: J. Chandran Kaimal
Meteorology Laboratory

Contract No. AF 19(628)-4076
Project No. 7655
Task No. 765501
Work Unit No. 76550101

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by

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ABSTRACT

A Continuous-Wave Three-Component Sonic Anemometer is described. The anemometer was developed for the Boundary Layer Branch of the Air Force Cambridge Research Laboratories by Bolt Beranek and Newman Inc. (BBN).

A physical description is presented, with several illustrations showing the construction of the anemometer and the manner in which it is mounted.

Design specifications are presented, and the operating procedure is described.

The theory of operation is discussed from the point of view of establishing performance limits on the anemometer.

The overall system is discussed and a detailed description of circuits is presented.

Instructions for operating the anemometer are presented.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
LIST OF FIGURES	vii
LIST OF TABLES	ix
1.0 INTRODUCTION	1
2.0 PHYSICAL DESCRIPTION	4
3.0 CONSTRUCTION	13
3.1 Probe	13
3.2 Electronics	14
4.0 SPECIFICATIONS	17
5.0 THEORY OF OPERATION	18
5.1 General Theory.	18
5.2 Performance and Design Parameters	22
5.3 Generation and Comparison of Coherent Anharmonic Signals	23
6.0 CIRCUIT DESCRIPTION	25
6.1 General	25
6.2 Description of Subassembly Circuits	28
6.2.1 Generator	28
6.2.2 Preamplifiers	30
6.2.3 Converter	30
6.2.4 Compensator.	33
6.2.5 Phasometer	33
6.2.6 Master Panel	36

TABLE OF CONTENTS (continued)

	Page
7.0 OPERATING PROCEDURE	38
8.0 ACKNOWLEDGMENTS	44
9.0 REFERENCES	45
APPENDIX A: Circuit Diagrams	A-1
APPENDIX B: Modifications of the Sonic Anemometer	B-1

LIST OF FIGURES

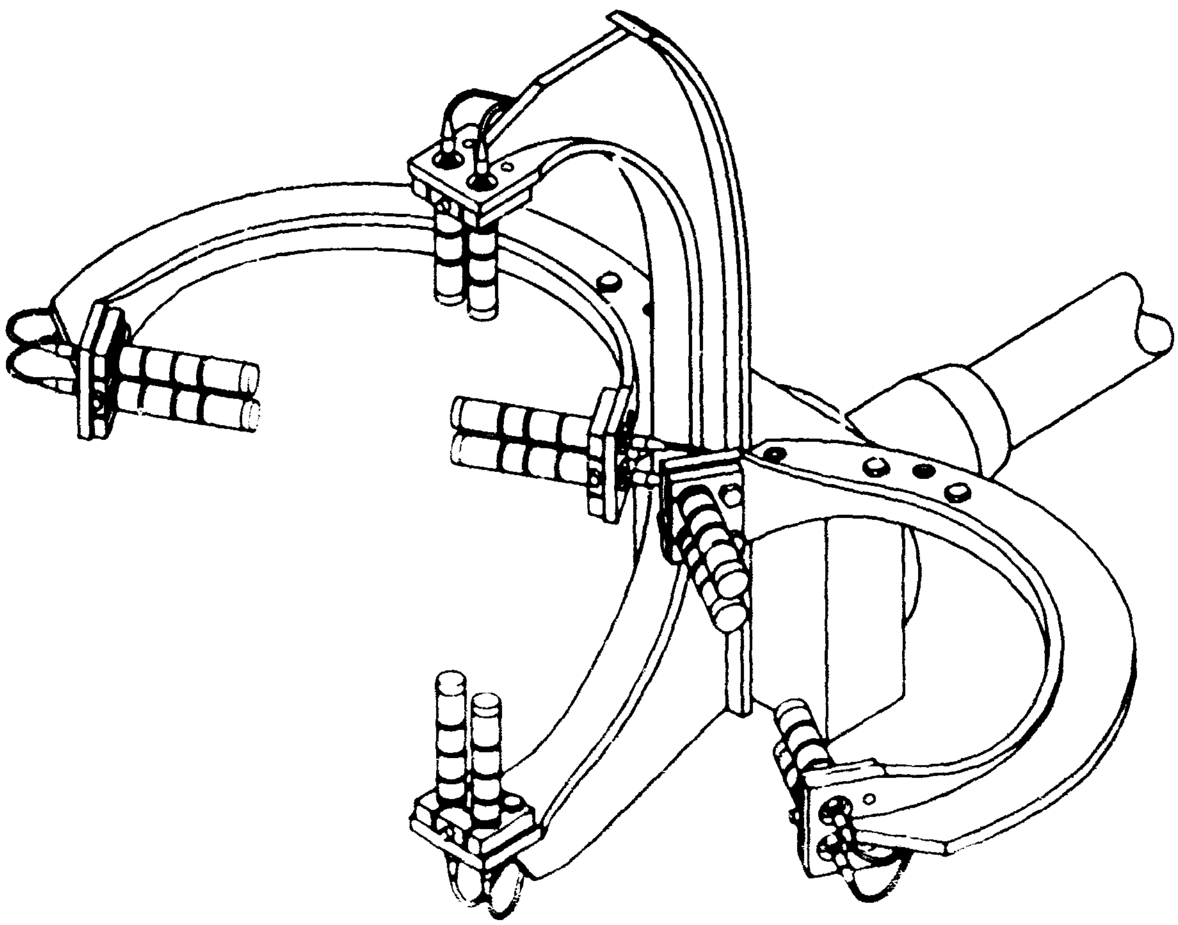
FIGURE		Page
1	Two Three-Component Continuous-Wave Sonic Anemometers Mounted on Meteorological Tower	5
2	Complete Three-Component Continuous-Wave Sonic Anemometer	6
3a	Anechoic Box Showing Mounting Hardware . . .	7
3b	Anechoic Box Showing Interior	7
4	Anemometer Probe: a. Windward Side. b. Rear View. c. With Alignment Rods. d. With Length Gauges.	9
5	Electronics Unit for Single Component of Sonic Anemometer	10
6	Spare Components Kit.	12
7a	Interior View of Electronics Assembly Showing Power Supplies	15
7b	Bottom View of Electronics Assembly	15
8	Electronics Subassembly Construction.	16
9	Typical Encapsulated Plug-In Modules.	16
10	Block Diagram of One-Component Sonic Anemometer .	26
11	Generator (Schematic)	29
12	Preamplifier (Schematic).	31
13	Converter (Schematic)	32
14	Compensator (Schematic)	34
15	Phasometer (Schematic)	35
16	Master Panel (Schematic).	37

LIST OF FIGURES (continued)

		Page
17	Front Panel of Electronics Unit for One Component of Sonic Anemometer	39
A-1	Amplifier 237C	A-2
A-2	Amplifier 237D	A-3
A-3	Clipper	A-4
A-4	ϕ Inverter	A-5
A-5	Bi-Polar	A-6
A-6	Dual Follower	A-7
A-7	Filter	A-8
A-8	Typical Phase Switch	A-9
A-9	30° Step Phase Shifter	A-10
A-10	Cambion FF-11-2	A-11
A-11	Cambion LT-11-1	A-12
A-12	Level Trigger Module (LT-31-1)	A-13
A-13	Flip-Flop Module FF-2	A-14
B-1	Modified Sonic-Anemometer Probe	B-3
B-2	Block Diagram of Modified One-Component Sonic Anemometer	B-4

LIST OF TABLES

TABLE		Page
1	Design Specifications	17



THREE-COMPONENT SONIC ANEMOMETER

1.0 Introduction

Moving-element anemometers (e.g., cup anemometers, bivanes, and microvanes) are unable to achieve the fast response necessary for studies of small-scale turbulence, because they are intrinsically limited by inertia and fragility and they tend to disturb the air about them. Fast-response wind measurement can be achieved with a sonic anemometer. The basic operating principle of a sonic anemometer is that the time required for sound to travel between fixed points through moving air is influenced by the motion of the air. A sound wave, propagating at the speed of sound in the air, is transported in the direction of the air's motion at the velocity of the air. Since the sound wave has no inertia, it is immediately responsive to fluctuations in the wind speed. Yet, the sound wave introduces a negligible perturbation of the air's state of motion.

Sonic anemometry was pioneered by Schotland[1] and Suomi.[2] In their experimental sonic anemometers, a pulse was propagated from a transmitter to a receiver, and the transit time of the pulse (usually a tone burst) was measured. These early workers encountered substantial difficulties in measuring transit time because the circuits used failed to determine accurately the leading edge of a pulse. The difficulty was believed to be due to dispersion of the sound wave during propagation through the air. This apparent failing of the pulse technique had a considerable influence on subsequent developments.

It was not until Gurvich's[3] work in the Soviet Union that a practical sonic anemometer was developed. Gurvich developed the use of continuous waves as a means of emitting and receiving sound without the difficulties of the pulse method. However, Gurvich found that the continuous-wave sonic anemometer presented a new problem. Because a continuous-wave signal is temporally homogeneous, the emitted and received signals of a sonic anemometer are not easily distinguishable when they have the same frequency. Gurvich solved this problem by using sets of signals of different frequencies, which he generated and compared by using a heterodyne system.

Meanwhile, in the United States, Kaimal and Businger[4] also worked on a continuous-wave sonic anemometer. Kaimal's work convinced him that the continuous-wave sonic anemometer was the principle candidate for successful fast-response anemometry. The anemometer described in this report is, in effect, a continuation of Kaimal's program.

Not all investigators turned to the use of continuous signals; some believed that the difficulties of the pulsed sonic anemometer were not intrinsic. Consequently, since 1960 two rival approaches have competed to develop a truly functional fast-response sonic anemometer: pulsed sonic amemometry and continuous-wave sonic anemometry. Mitsuta,[5] working at Kyoto University in Japan, developed an improved pulse-delay sonic anemometer (available commercially from Kaijo Denki[6]). Beaubien[7] also worked on a pulsed sonic anemometer. Beaubien had tried a continuous-wave sonic anemometer, but after encountering considerable difficulties in the design of effective transducers, he turned to the pulse technique.

The result of these investigations is that, at present, there exist several sonic anemometers in addition to the one described in this report. One, the Mitsuta anemometer, is commercially available. It and the Beaubien anemometer (soon also to be commercially available) are pulsed sonic anemometers. The instrument that we have developed is a continuous-wave three-component sonic anemometer. Two three-component units have been used during two years of an ongoing field program.[8] These are the most extensive measurements made in the United States* using a continuous-wave anemometer.

*In the Soviet Union, all measurements are taken with continuous-wave sonic anemometers.

2.0 Physical Description

The complete sonic anemometer consists of a probe that transmits and receives acoustic signals and electronic circuitry that provides driving signals to the probe and that processes the received signals.

Figure 1 shows a pair of three-component sonic anemometers mounted on a meteorological tower at Liberal, Kansas, the site of Project Windy Acres.[8] Each anemometer is held away from the tower by a 6 ft boom that can be oriented to enable the open part of the anoemometer probe to face into the prevailing wind.

Electronic circuitry for the anemometer is contained in aluminum cases, one for each wind component. A three-component-anemometer system is shown in Fig. 2. A single cable, long enough to extend the length of a boom, is connected from the probe to the three cases. In Fig. 2, the case in the foreground is closed to show a standpipe inlet that is used to allow the closing of the case against the weather while the anemometer is operating. Note, in Fig. 1, that an anechoic box is mounted on the tower at each of the two levels. The anechoic box is used to obtain a zero set. The boom is swung inboard so that the anemometer sits in the box. More-detailed photographs of the anechoic box are shown in Fig. 3. Figure 3(a) shows the box closed; the mounting brackets clamp onto a vertical member of the tower. Vertical displacement and rotational orientation are adjusted so that the anemometer fits into the box when the boom is swung inboard. Figure 3(b) shows the box opened. The interior of the box is covered with sound-absorbing material to reduce reflections.

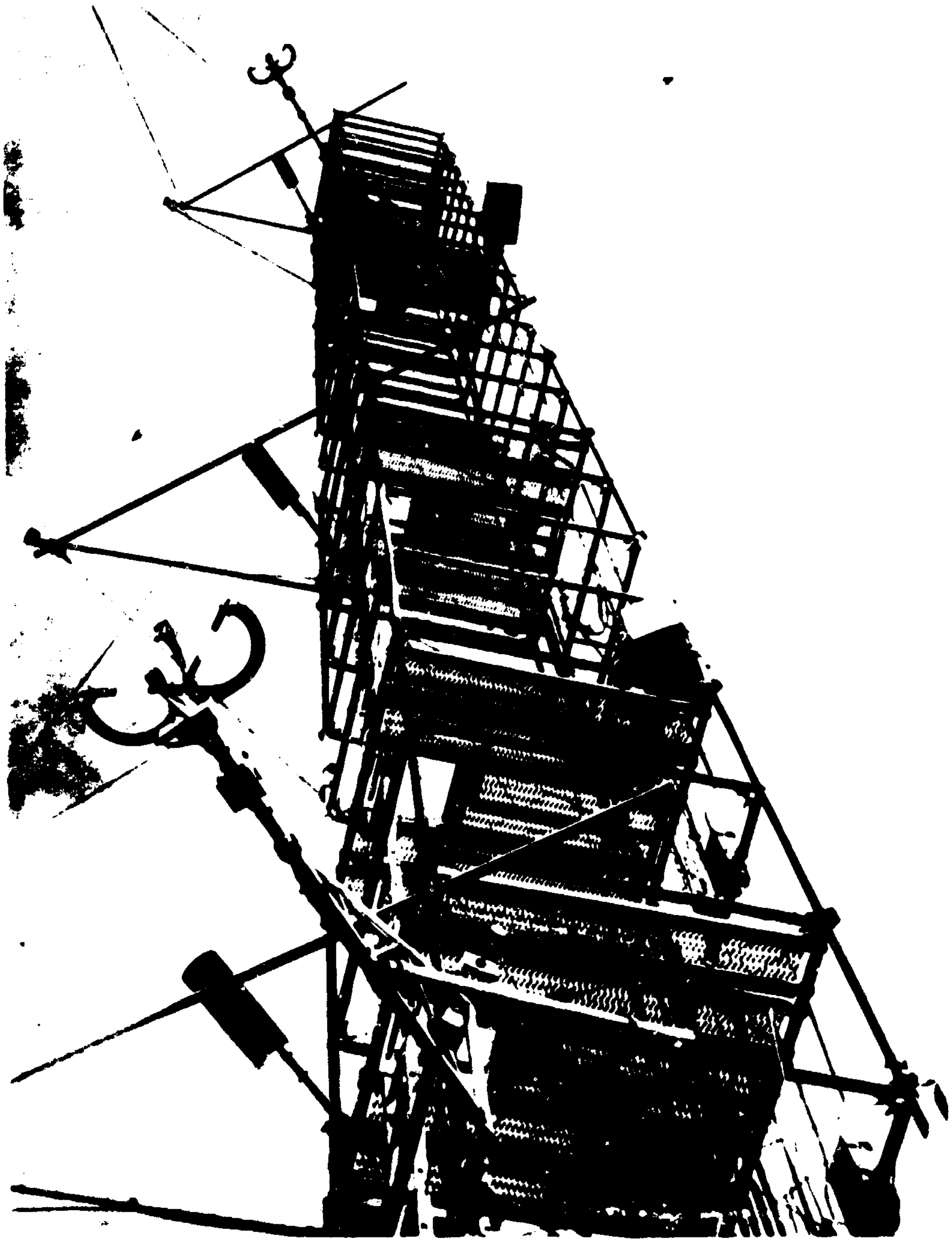


FIG. 1 TWO THREE-COMPONENT CONTINUOUS-WAVE SONIC ANEMOMETERS MOUNTED ON METEOROLOGICAL TOWER

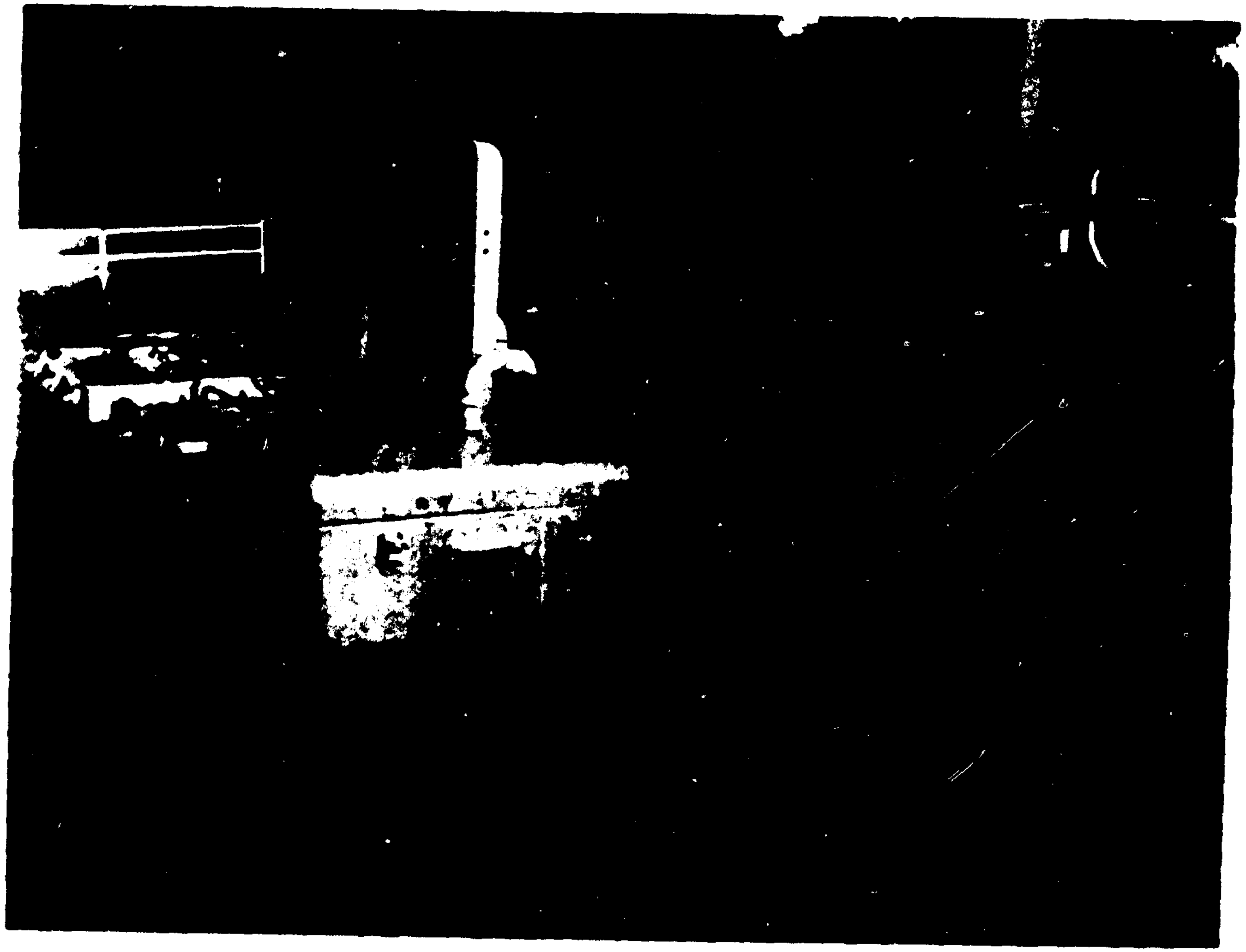


FIG. 2 COMPLETE THREE-COMPONENT CONTINUOUS-WAVE SONIC ANEMOMETER

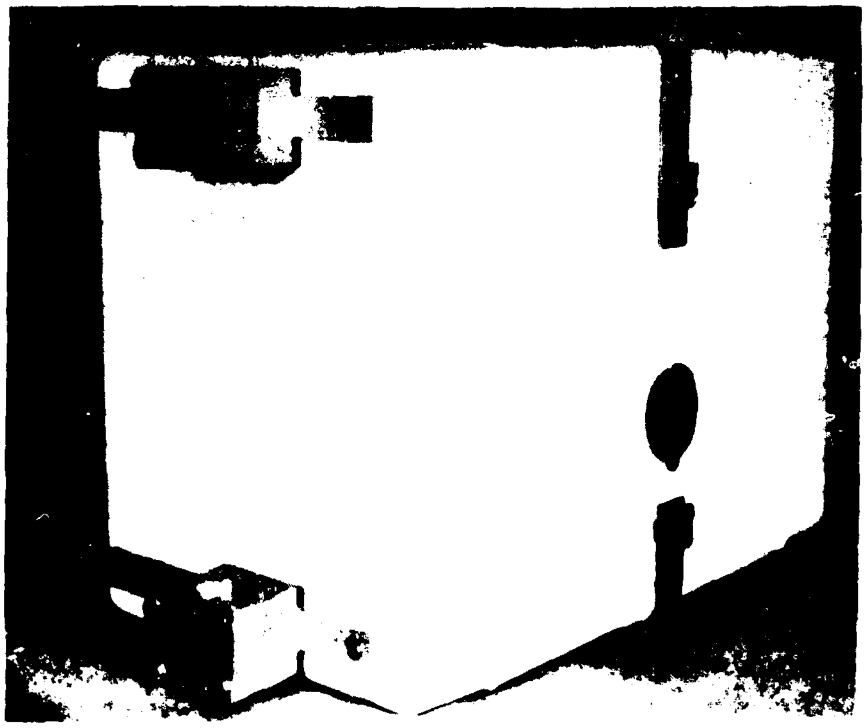


FIG. 3a ANECHOIC BOX SHOWING MOUNTING HARDWARE

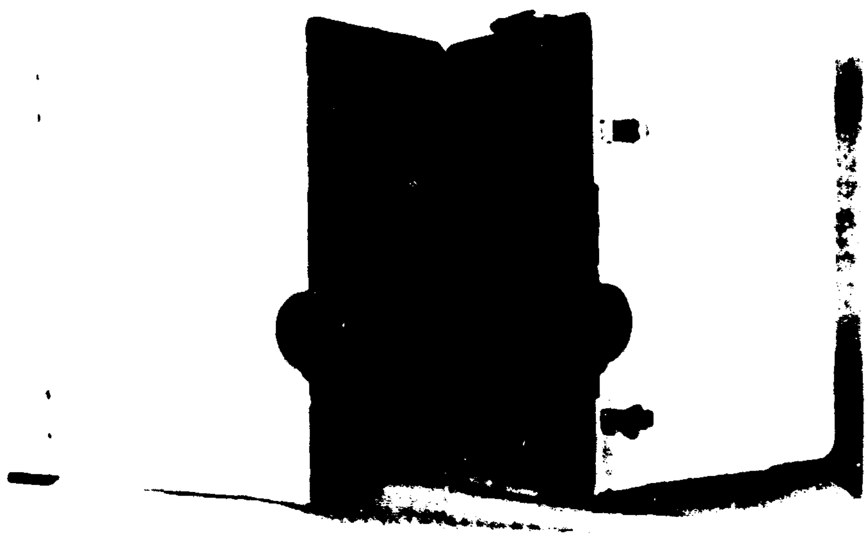


FIG. 3b ANECHOIC BOX SHOWING INTERIOR

A view of the windward side of the anemometer probe (the sensing head) is shown in Fig. 4(a). Each component of the wind is measured by two pairs of transducers - one emitter/receiver pair for propagating sound in a given direction and a second pair for propagating sound in the opposing direction. The vertical transducer separation is 20 cm and the horizontal separation is 10 cm. Note that the horizontal axes form an angle of 120°, thus presenting a more open aspect of the probe windward than would axes at 90°. (Signals proportional to components of the wind along the boom axis and transverse to the boom axis can be obtained by linear combinations of the processed signals from the horizontal paths.)

The rear of the anemometer probe is shown in Fig. 4(b). A flanged hub is attached to the machined rear surface of the connector box of the probe. The hub is in turn, attached to the boom. Note the level machined surface on the top side of the junction box for a level indicator (not shown in the photograph).

The sonic anemometer is supplied with sets of gauges and spare components. To align the emitter/receiver sets for each axis, one inserts the alignment rods, as shown in Fig. 4(c) and adjusts the positions of the transducer mounting blocks. To adjust the transducer separation in order to obtain the proper pathlength for each wind component, one uses the length-adjustment gauges that are shown in position in Fig. 4(d).

Figure 5 shows the electronics unit for a typical channel for measuring one component of the wind. The inlet hole in the cover is for a standpipe through which the cables enter. The cables provide connections for two receivers and two emitters. There are also connections for the windspeed output, the power line, and remote-control operations.

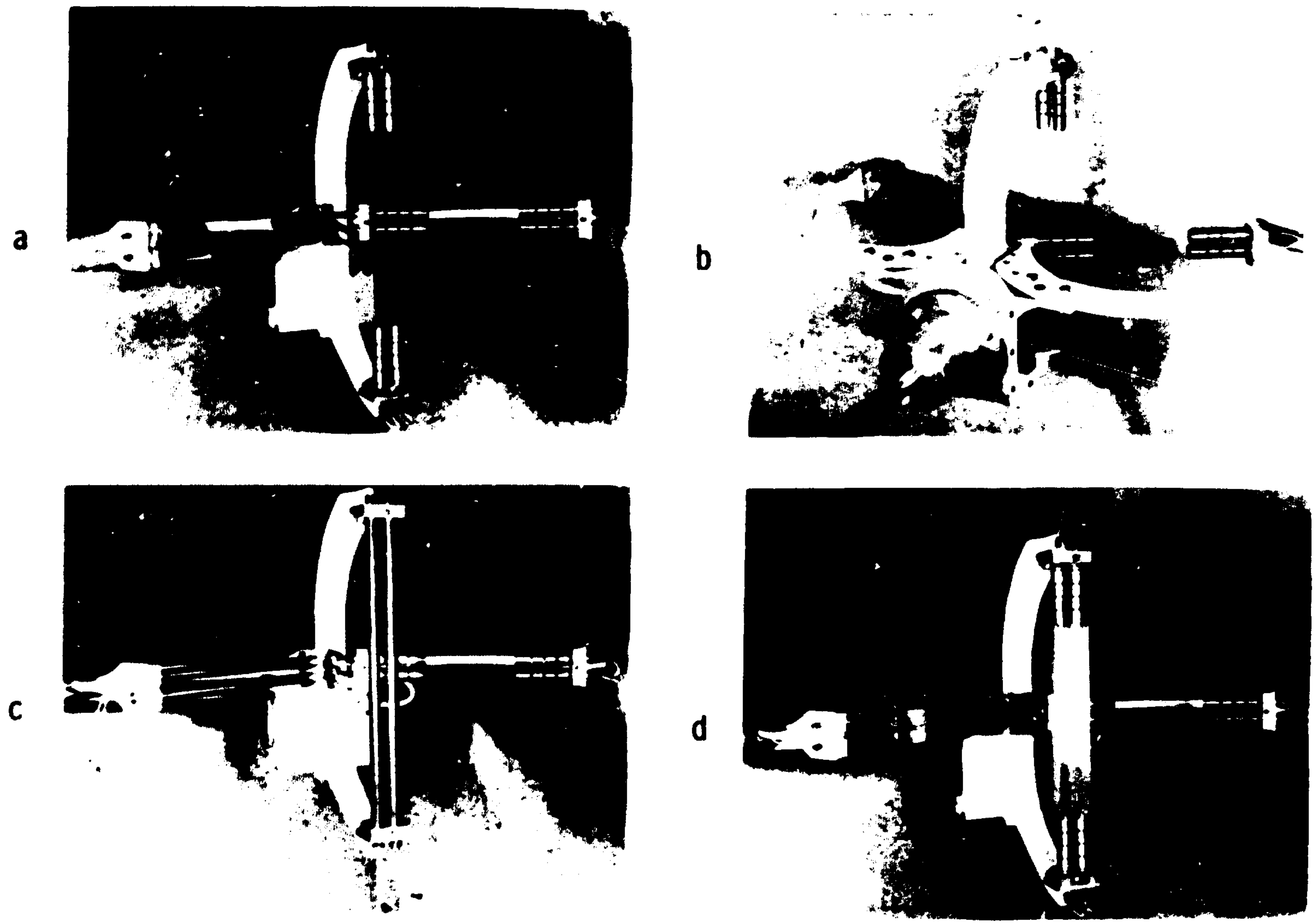


FIG. 4 ANEMOMETER PROBE: a. WINDWARD SIDE. b. REAR VIEW. c. WITH ALIGNMENT RODS. d. WITH LENGTH GAUGES.

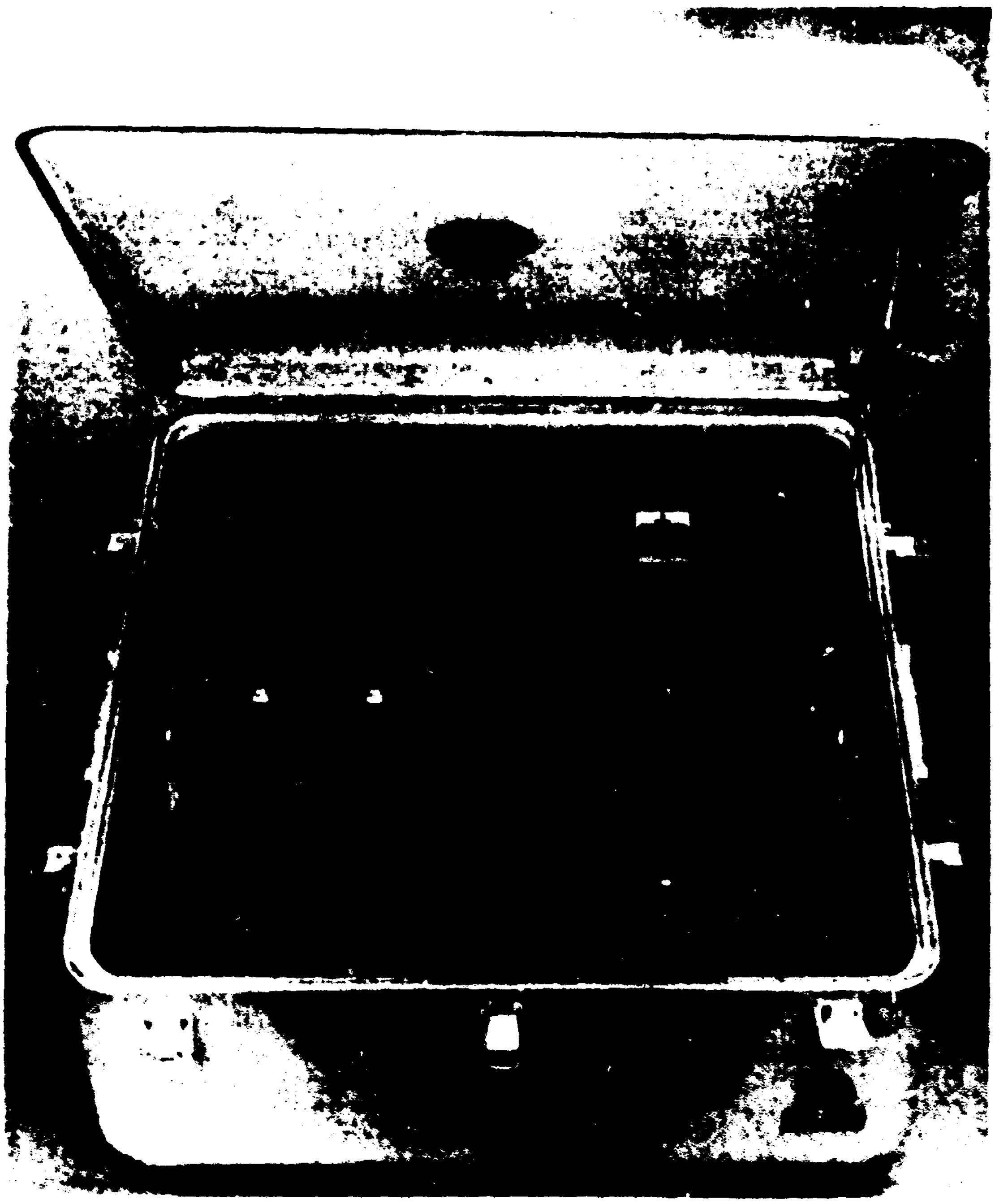


FIG. 5 ELECTRONICS UNIT FOR SINGLE COMPONENT OF SONIC ANEMOMETER

A complete set of spare transducers and a complete set of essential, spare electronic components are provided. The spare electronic components consist principally of encapsulated circuits. Figure 6 shows the spare-components kit.

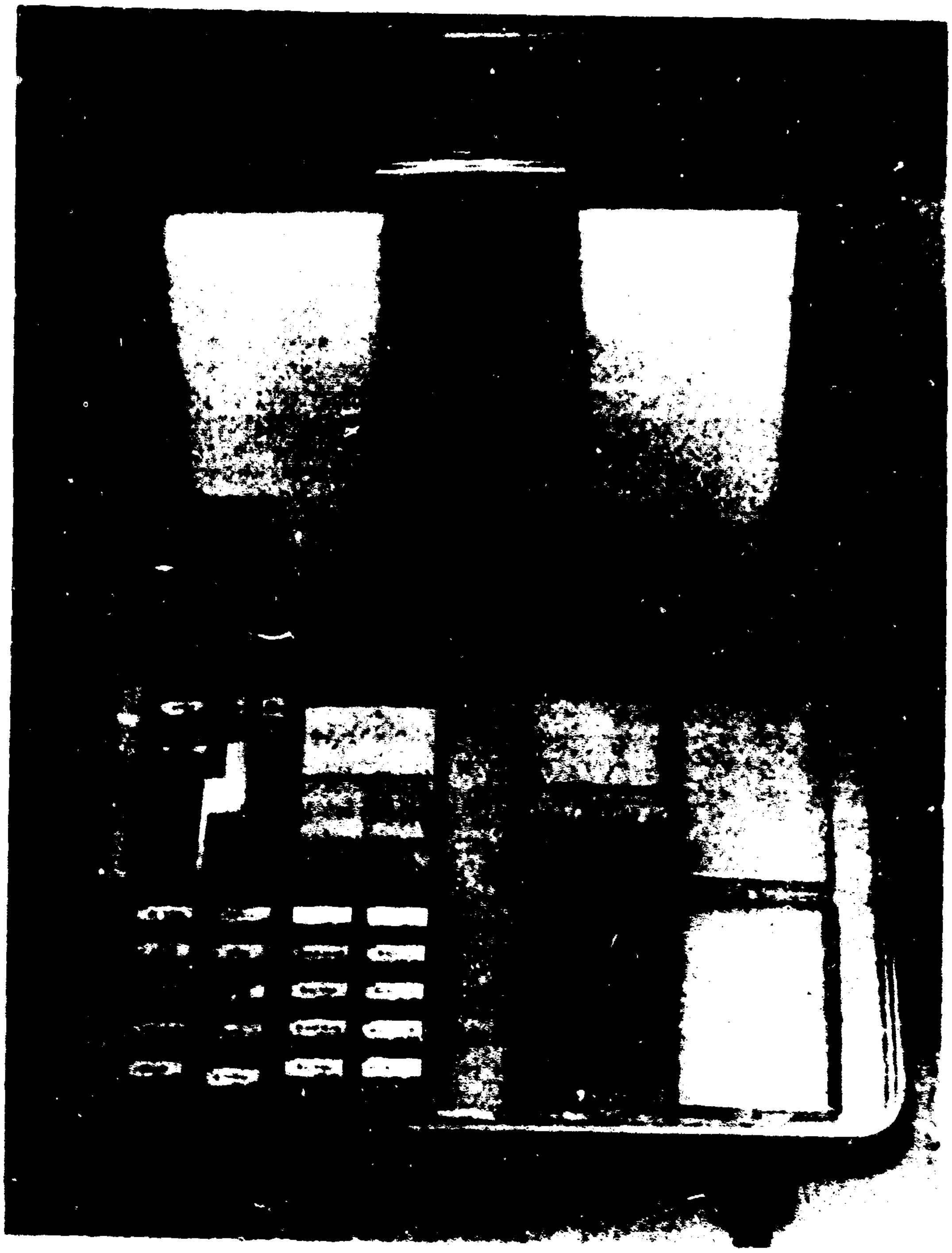


FIG. 6 SPARE COMPONENTS KIT

3.0 Construction

3.1 Probe

The probe (Fig. 4) is constructed of machined and welded anodized aluminum and is finished in baked, white enamel. The transducers are mounted in adjustable blocks. All mating surfaces are machined so that the two horizontal arms of the anemometer probe are in the same plane as the top surface of the junction box, which, in turn, is perpendicular to the machined rear surface. Also, the vertical members of the anemometer probe are milled to make a precise 90° angle with respect to the horizontal components.

Cables, connected to the transducers by Microdot connectors are run to the junction box along the leeward side of the probe structure; there, they are soldered to coaxial connectors that are mounted and sealed with silicone rubber in a phenolic block.

The transducers are hermetically sealed. The sensitive element is a bimorph consisting of a circular plate to which is epoxied a piezoceramic disk. Between the sensitive element and the mounting end of the transducer is a mechanical filter that prevents the excitation of the emitter from being mechanically coupled to the receiver. The mounting end of the transducer is sheathed in phenolic to avoid electrical grounding of the case at the mounting point (all grounds are made at the electronic control units). The phenolic-sheathed mounting end is clamped in the mounting block such that the transducer extension along its axis is adjustable, thereby permitting precise adjustment of the pathlength. The transducers in the vertical axis are made of brass and those in the horizontal axes are made of aluminum.

The anechoic box (Fig. 3) is lined with a polyurethane foam that has high absorptivity in the frequency range of interest. The box is made of fiberglass, hinged at one side, and rubber-gasketed at the inlet where the boom that holds the probe fits. Positive-locking clamps secure the box tightly about the anemometer probe.

3.2 Electronics

The electronic units are mounted in extruded aluminum cases 19-1/2 × 20-1/2 × 10-3/8 in. The cases have hinged covers, locking lid stops, and are gasketed and provided with clamps so that they are hermetically sealed when clamped shut. The modular electronic assembly (see Fig. 5) consists of a power supply in the main chassis and six interconnected subassemblies. Fig. 7(a) shows the contents of the extruded aluminum case, and Fig. 7(b) indicates how the six subassemblies fit into the main chassis. Note that the subassemblies are permanently wired with flexible cables; hence, they can be pulled out for examination, but they cannot be completely detached from the main unit.

The construction of a subunit is shown in Fig. 8. Each subunit has a single circuit board on which discrete components and encapsulated plug-in circuits are mounted. Examples of some of the units are shown in Fig. 9.

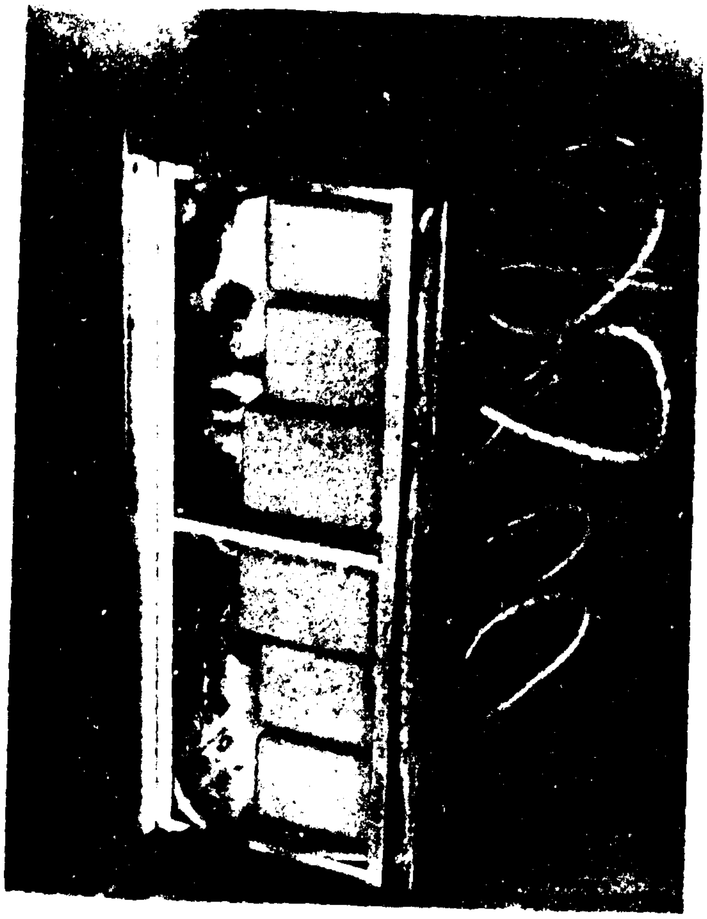


FIG. 7a INTERIOR VIEW OF ELECTRONICS ASSEMBLY SHOWING POWER SUPPLIES

FIG. 7b BOTTOM VIEW OF ELECTRONICS ASSEMBLY

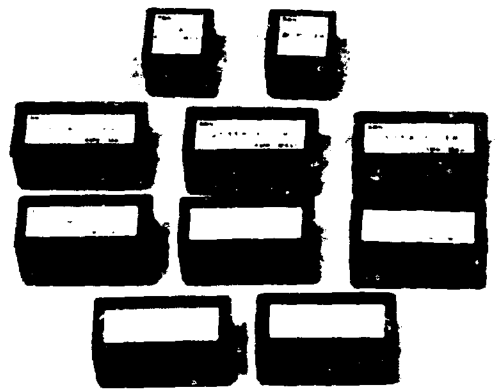


FIG. 8 ELECTRONICS SUBASSEMBLY CONSTRUCTION

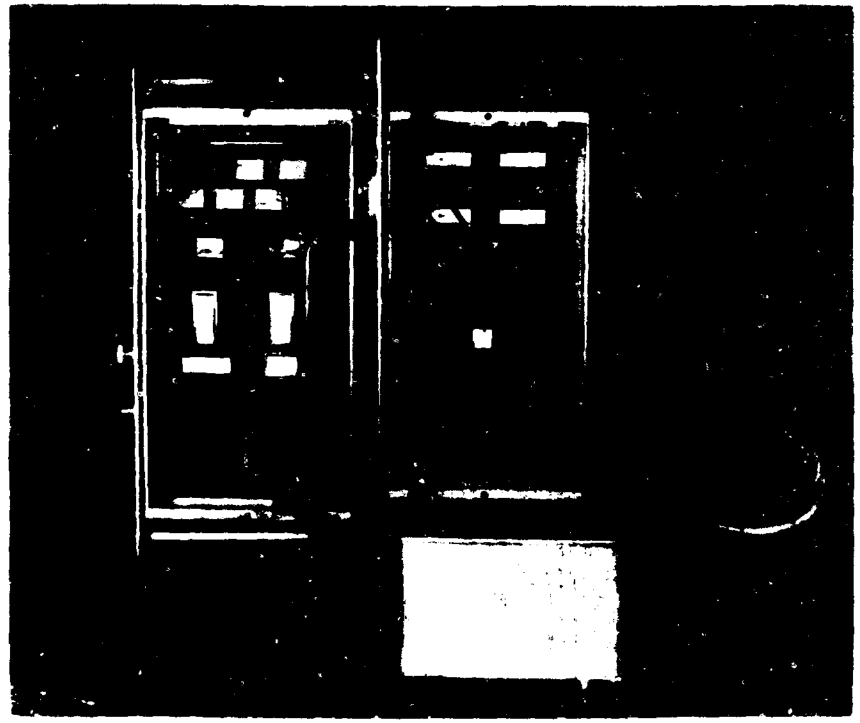


FIG. 9 TYPICAL ENCAPSULATED PLUG-IN MODULES

4.0 Specifications

Design specifications* for the anemometer are presented in Table 1.

TABLE 1. Design Specifications.

Wind-speed range:	
vertical axis	-4 to +4 m/sec
left horizontal axis	-16 to +16 m/sec
right horizontal axis	-14 to +14 m/sec
Output analog voltage	-10 to +10 V each axis
Output meter	One each channel provided with slow-response switch and scale-expand switch
Speed of response	Half-power point at 25 Hz[a]
Noise and drift at constant temperature	< 1% of full scale
Output impedance of analog voltage	< 1 Ω
Recommended load	10,000 Ω
Recommended maximum cable length	750 m
Remote-control capability	zero test, ± full-scale test
Remote-control requirements	3-wire cable (closures required)
Power requirements	117 V rms, 60 Hz ac, 100 W for each channel

[a]The speed of response is limited to approximately 250 Hz by the bandwidths of the circuits and the transducers. The 25-Hz cutoff has been intentionally imposed; the cutoff of any channel can be changed by the replacement of a single capacitor.

*Actual performance specifications under realistic operating conditions will be reported following reduction of the data taken in Project Windy Acres.

5.0 Theory of Operation

5.1 General Theory

According to geometrical acoustics, the propagation time τ of an acoustic disturbance from a point r_1 to a point r_2 is given by[9]

$$\tau = \int_{\underset{\sim}{r}_1}^{\underset{\sim}{r}_2} ds(1-\underset{\sim}{\mu}\cdot\underset{\sim}{n})/c \quad , \tag{1}$$

where c is the speed of sound in still air, $\underset{\sim}{\mu} = \underset{\sim}{u}/c$ is the Mach number ($\underset{\sim}{u}$ is the wind velocity), and $\underset{\sim}{n}$ is a unit vector along the acoustic path. The integration is over the proper refractive path, which is obtained by solving the Euler/Lagrange equations that solve the variational problem of Fermat's principle[10], $\delta\tau = 0$. Equation 1 is derived on the assumption that the space and time variations of $\underset{\sim}{\mu}$ are of considerably larger scale than the wavelength and period of the acoustic disturbance (the derivation is also based on $\mu^2 << 1$).

For a short-pathlength sonic anemometer, a further simplifying assumption is possible: the refractive path is not significantly distinguishable from the geometrical straight line joining the emitter and the receiver. Consequently, the propagation time takes the form

$$\tau = \frac{|r_2 - r_1|}{c} - \frac{1}{c}\int_{\underset{\sim}{r}_1}^{\underset{\sim}{r}_2} dr\cdot\mu(x,y,z,t) \quad , \tag{2}$$

where now the path of integration is along the line joining r_1 and r_2 .

The standard derivation of the sonic-anemometer equation does not begin with Eq. 2 but with the geometrical relationship that describes an outgoing spherical wave in a uniform wind field. The resulting expression for the difference in transit times of opposing propagation is

$$\Delta\tau = \frac{2\ell \underset{\sim}{u} \cdot \underset{\sim}{n}}{c^2} \quad , \tag{3}$$

where u·n is the projection of the uniform constant wind on the anemometer axis of length ℓ. In the more precise theory, Eq. 2 leads to

$$\Delta\tau = \frac{1}{c^2} \left(\int_{\underset{\sim}{r}_1}^{\underset{\sim}{r}_2} d\underset{\sim}{r} \cdot \underset{\sim}{u} + \int_{\underset{\sim}{r}'_1}^{\underset{\sim}{r}'_2} d\underset{\sim}{r} \cdot \underset{\sim}{u} \right) \quad , \tag{4}$$

where the nonuniformity of the wind field requires the explicit introduction of r_2' and r_1' to represent the discrepancy in path of the two emitter/receiver pairs. Of course, the pathlengths must be the same in a properly designed anemometer; i.e., $|r_2 - r_1| = |r_2' - r_1'|$. Hence, in writing Eq. 4 this property has been used.*

Equations 3 and 4 can be reconciled only if we take the wind field $\underset{\sim}{u}$ to be uniform. In reality, the wind field is nonuniform, and this forces us to determine if there are any consequences of using Eq. 4, instead of Eq. 3, that are of importance in the design and operation of a sonic anemometer.

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*Note the practical necessity of careful adjustment of the transducer-separation distance; if the pathlengths are unequal, a first-order temperature dependence is introduced.

One result that we obtain by considering the nonuniform wind field is the establishment of an eddy-scale cutoff for the sonic anemometer. To avoid unnecessary complication, we can set $\underset{\sim}{r}'_2 = \underset{\sim}{r}_2$ and $\underset{\sim}{r}'_1 = \underset{\sim}{r}_1$; i.e., we can make the opposing paths coincident. Then, using the time and space Fourier transform of the wind field, we can write Eq. 4 in the form

$$\Delta\tau = \int_{-\infty}^{+\infty} d\omega \iiint_{-\infty}^{+\infty} d^3k \, \frac{2}{c^2} \, \underset{\sim}{w}(\underset{\sim}{k},\omega) \cdot \int_0^{\ell} d\underset{\sim}{r} \, e^{i\underset{\sim}{k}\cdot\underset{\sim}{r} - i\omega t} \tag{5}$$

where $\underset{\sim}{w}(\underset{\sim}{k},\omega)$ is the amplitude spectrum of $\underset{\sim}{u}\cdot\underset{\sim}{n}$ in wavenumber frequency space. By taking the decomposition of the wind-velocity spectrum in a coordinate system for which the anemometer path is one axis, say the x axis, the transit-time difference takes the form

$$\Delta\tau = \frac{2}{c^2} \int_{-\infty}^{+\infty} dk_x \left(\frac{\sin k_x \ell/2}{k_x \ell/2} \right) w_x(k_x, y, z, t) \quad . \tag{6}$$

Equation 6 shows that the response of the anemometer to the wind turbulence is weighted such that higher wavenumbers in the eddy spectrum of the wind component along the anemometer axis are attenuated. The half-power point is reached when the eddy scale Λ and the anemometer pathlength ℓ have the relationship

$$\frac{\ell}{\Lambda} = \frac{1.4}{\pi} \quad . \tag{7}$$

Equation 7 is the basis for determining the pathlength requirement ℓ for a one-component sonic anemometer, that is to measure velocity fluctuations that are due to eddies having a dimension along the path larger than a scale of Λ.

Another relationship that can be derived from Eq. 4 concerns crosstalk, i.e., the sensitivity of a one-component anemometer to wind fluctuations that are normal to the anemometer axis. The derivation is not presented here; however, it follows an analysis similar to the one presented above. The crosstalk ratio R expresses the ratio of cross-wind response to on-axis response.

$$R = \tan k_y \Delta/2 \quad , \tag{8}$$

where k_y is a wavenumber of the transverse wind component and Δ is the lateral separation between the two paths of the one-component anemometer. The sharp rise of the tangent with increasing argument indicates that the fine structure in the response of an anemometer should be critically evaluated to determine if the response is not caused by the transport of eddies of small scale (Λ_y <32Δ for 10% crosstalk) across the anemometer path.

If one assumes that the lateral separation Δ is fixed by consideration of mechanical and aerodynamic design, then the crosstalk limitation and the expected maximum wind speeds can be combined by using Taylor's hypothesis (frozen turbulence) to establish a response-time requirement for the anemometer. The minimum response time τ_r, the maximum wind speed $|V|_{max}$, and the 10% crosstalk eddy scale 32 Δ obey

$$1/\tau_r = |V|_{max}/32\,\Delta \quad . \tag{9}$$

Axis lengths ℓ of 20 cm for the vertical axis and 10 cm for each of the horizontal axes were chosen in accordance with the eddy-scale cutoff condition defined in Eq. 7 and the intended use of the instrument. A lateral path separation Δ of 4 cm was chosen because of the physical size of the transducers and the mounting block. The response-time cutoff was determined at $1/\tau_r = 25$ Hz on the basis of Eq. 9, with an anticipated $|V|_{max}$ of 16 m/sec (horizontal axis) and a value of 4 cm for Λ.

Consider next the computation of the frequencies of the sonic signals that are required in a continuous-wave sonic anemometer. Time difference $\Delta\tau$ is converted to phase ϕ by multiplying Eq. 3 by $2\pi f$, where f is the sonic frequency. The maximum full-scale phase is $\pm\pi$ rad. The frequency-determining equation is

$$f = c^2/(4\ell V_{max}) \quad , \tag{10}$$

where V_{max} is the maximum wind speed for the axis under consideration.

5.2 Performance and Design Parameters

The key parameters of the anemometer are determined by the equations discussed above.

The sonic frequencies are computed from Eq. 10, using c^2 for dry air at 25°C* (Ref. 11). In the vertical axis, the anticipated $|V|_{max}$ is 4 m/sec; hence f = 35 kHz. For the horizontal axes ($|V|_{max}$ = 16 m/sec), different signal frequencies must be used for the lefthand and righthand arrays to avoid interference. Hence, we chose f = 20 kHz for the left horizontal channel and f = 16.5 for the right horizontal channel. The corresponding $|V|_{max}$ are approximately 15 m/sec and 18 m/sec.

---

*c^2 = 119,920 $(m/sec)^2$.

If there is to be no interference, signals propagating along opposing paths must be of different frequencies. However, the two signals of each component must be phase-coherent. A unique system based on anharmonic phase-coherent signals is used. Thus there are three additional frequencies. We have taken these additional frequencies to be two-thirds of the three values discussed above for several technical reasons involving simplifying the instrument design. In summary, the required frequencies are the following:

Channel	Frequency
vertical	35 and 23-1/3 kHz
left horizontal	20 and 13-1/3 kHz
right horizontal	16.5 and 11 kHz

5.3 Generation and Comparison of Coherent Anharmonic Signals

Consider now the function of the anemometer transducers and circuitry. For each wind component, signals are to be propagated in opposing directions, received, and their phase compared to produce an output proportional to their phase difference ϕ, which, according to Eq. 3, is proportional to the wind speed. The frequencies of the oppositely propagated signals are f_1 and $f_2 = 2f_1/3$. Hence, it is necessary to generate and compare coherent, anharmonically related signals.

Coherence is achieved by generating signals of frequencies f_1 and f_2 from the same oscillator. Anharmonicity is achieved by successive divisions and multiplications. Comparison of the anharmonic signals is achieved by additional multiplications and divisions that convert signals at frequencies f_2 to signals at the

the frequency f_1. Ambiguities of phase created in the frequency conversion are restored by a phase-lock circuit. The signals of frequencies f_1 and f_2 (originally f_2 but transformed to f_1) are compared in a phase-comparison circuit.

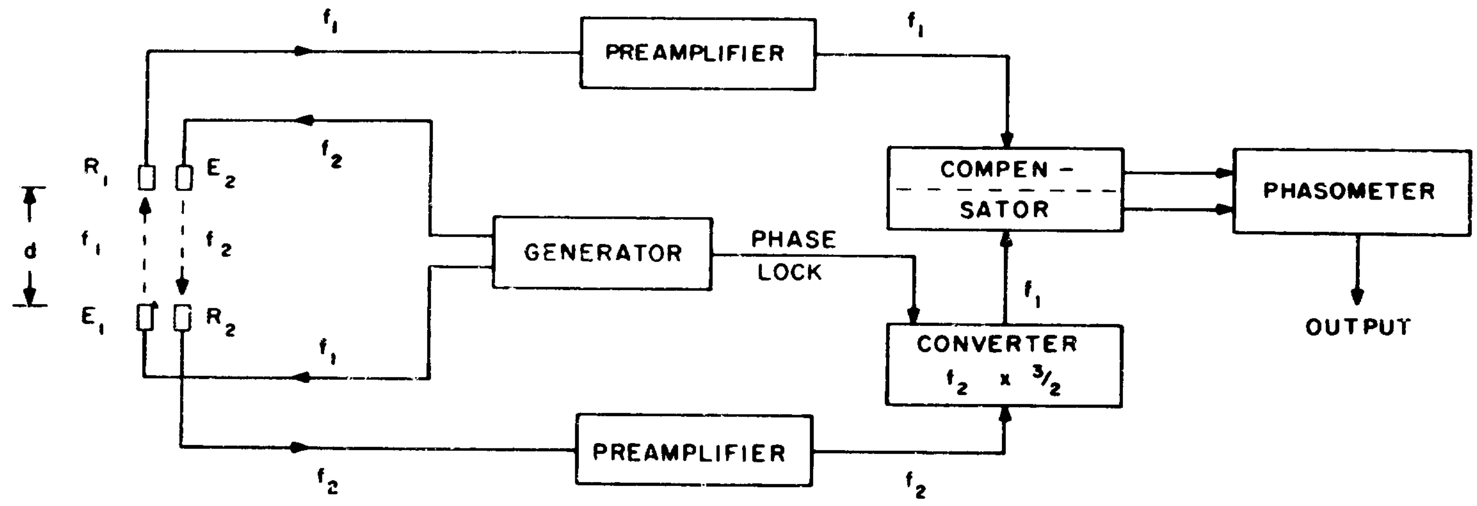
6.0 Circuit Description

6.1 General

A block diagram of a single channel of the anemometer is shown in Fig. 10; the blocks represent the six subunits. The ***generator*** produces the signals at pairs of frequencies listed in the table in Fig. 10. A pulse is also generated at repetition frequency $f_1/3$, which is used for phase locking. The signals are supplied to the emitters (the phase-lock signal goes to the converter).

The signals, received by the opposing receivers, are filtered by the narrow-band response (approximately 250 Hz) of the transducers. The signal from the receivers is supplied to the ***preamplifier*** which consists of a sequence of narrow-band amplifiers and amplitude limiters. The preamplifiers also provide means to shift the phase of the output of the amplifier with respect to the input. The purpose of the preamplifiers is to produce signals with standardized amplitudes and adjusted phases.

The signal at frequency f_2 is supplied to the input of the ***converter***. The purpose of the converter is to multiply the frequency of the input by 3/2. A bistable halves the frequency. The bistable is reset by the phase-lock pulse (if it slips out of step) to keep the frequency-divided signal in proper phase relationship with the source signal. A filter, tuned to the third harmonic of the output of the bistable achieves multiplication by three. Hence, the bistable and filter accomplish frequency multiplication by 3/2. The converter produces a standardized signal level at frequency f_1.



NOTE: E_1 AND R_1 TUNED TO FREQUENCY f_1, E_2 AND R_2 TUNED TO FREQUENCY f_2

COMPONENT	f_0	f_1	f_2	d	NOM. RANGE
V_1	80 Hz	20 Hz	13 1/3 Hz	10 CM	± 14 M/SEC
V_2	66 Hz	16 1/2 Hz	11 Hz	10 CM	± 16 M/SEC
W	70 Hz	35 Hz	23 1/3 Hz	20 CM	± 0.4 M/SEC

FIG. 10 BLOCK DIAGRAM OF ONE-COMPONENT SONIC ANEMOMETER

One input of the *compressor* is from the converter. The other input to the compensator derives from the preamplifier that amplifies the signal of frequency f_1. The compensator consists of amplitude-stabilizing circuits, an adjustable phase shift, and a tuned amplifier. The purpose of the compensator is to compensate all instrumental phase shifts, particularly those occurring in the tuned circuits, so that the combination of the phasometer and the compensator is a properly calibrated phase-measuring device. The compensator also contains relays and a front panel switch which can be used to connect (1) exactly in phase signals to the two channels or (2) exactly out of phase signal to the two channels. Thus, the relays operate zero and full-scale positive and negative checks on the system.

The compensator supplies the signals to the *phasometer*. The phasometer is a pulse-integrating, phase-measuring circuit. It consists of input-limiting amplifiers, level triggers, and a bistable which is caused to change state alternately by the signals from the two channels. The output is obtained from an operational-amplifier integrator for which the time constant is chosen to have a cutoff of approximately 25 Hz. The phasometer also has a front-panel meter, an expanded-scale switch, and a meter-response switch. The meter-response switch allows one to slow the meter response substantially so that the mean wind can be observed in the presence of severe fluctuations. The expanded-scale switch gives an approximate 10:1 scale change so that the meter can be used for zero setting and other calibration adjustments. The output of the phasometer is at a coaxial connector on the front panel; it can be connected (via a cable) to a recorder or computer to which it supplies a voltage proportional to wind speed.

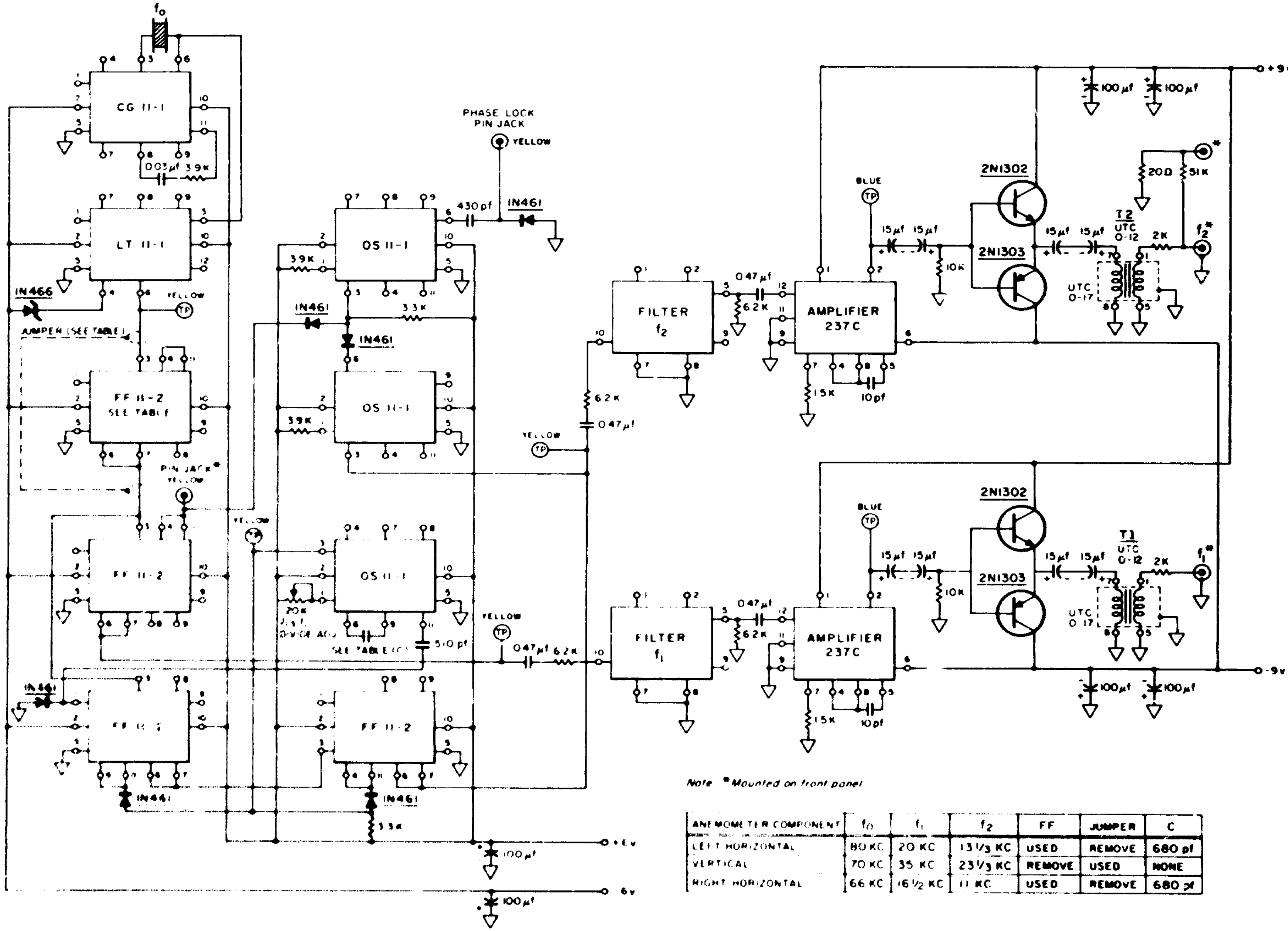
6.2 Description of Subassembly Circuits

6.2.1 Generator

The circuit diagram of the generator is shown in Fig. 12. The clock generator CG 11-1 (Fig. 11, top lefthand corner) and the crystal connected across Terminals 3 and 6 function as an oscillator that generates a signal of frequency $2f_1$ (or $4f_1$). A level trigger LT 11-1 connects with the clock generator to shape the oscillator output. The pulses from the level trigger are supplied to a series of one or two flipflops according to the frequency of the oscillator (see Table at the bottom of Fig. 11). One output of the flipflops, a signal of frequency f_1, is filtered, amplified, and supplied through a pair of emitter followers and a transformer to the f_1- output terminal. The output can drive 2000 Ω at 15 V.

An additional pair of flipflops (Fig. 11, bottom left) and the OS 11-1 one shots form a divide-by-three circuit. The divider is supplied directly with the signal of frequency $2f_1$. The resulting signal of frequency $2f_1/3$ is also filtered, amplified, and supplied through a pair of emitter followers and a transformer to the $2f_1/3$ output, which is also capable of driving 2000 Ω at 15 V. The other pair of one shots is used to establish the phase-lock pulse (available at a pinjack to the rear of the chassis).

The signals from the generator drive the transmitters. The resulting acoustic signals are picked up by the receivers, which are connected to the preamplifiers.



Note *Mounted on front panel

ANEMOMETER COMPONENT	f_0	f_1	f_2	FF	JUMPER	C
LEFT HORIZONTAL	80 KC	20 KC	13 1/3 KC	USED	REMOVE	680 pf
VERTICAL	70 KC	35 KC	23 1/3 KC	REMOVE	USED	NONE
RIGHT HORIZONTAL	66 KC	16 1/2 KC	11 KC	USED	REMOVE	680 pf

FIG. 11 GENERATOR (SCHEMATIC)

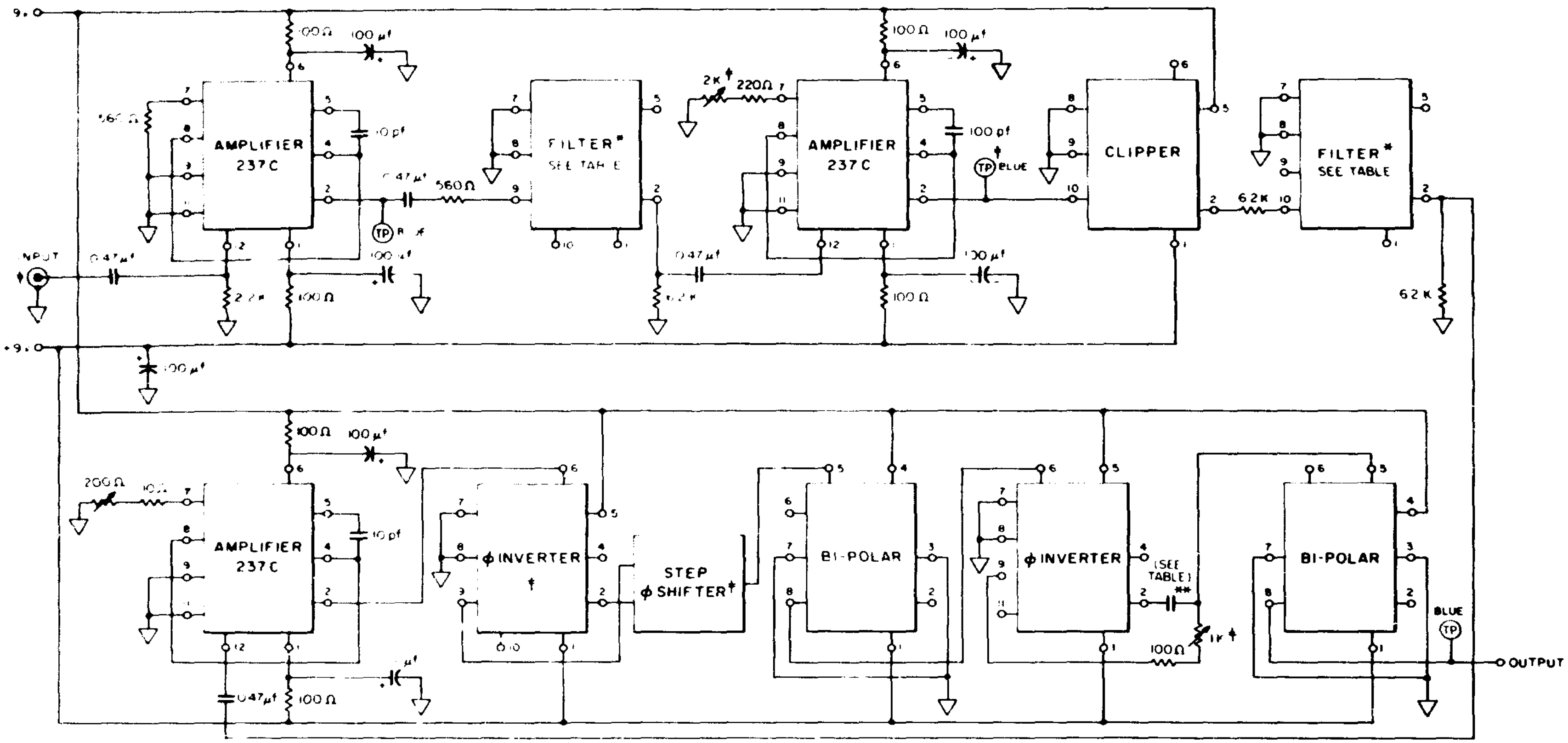
6.2.2 Preamplifiers

A preamplifier schematic is shown in Fig. 12. The input is supplied to the sequence: low-noise amplifier, filter, and amplifier. The output is available at a pinjack. A screw-driver-adjusted potentiometer provides a means for gain adjustment. The amplifier/filter/amplifier configuration raises the signal to an adequate level to drive a clipper that preserves only that part of the waveform which is close to the zero crossing. A filter, following the clipper, receives the pulselike waveform. The output of the filter is again a sine wave, but of stabilized amplitude. The signal amplitude is restored by the next amplifier.

The remaining circuit of the preamplifier is a two-gang phase shifter. The first phase shifter can be used to step the phase through 30° increments. A vernier adjustment can adjust the phase by increments within the 30°. *ϕ inverters* and *bipolars* drive and terminate the phase shift RC networks. The final output of each preamplifier is a sine wave at standardized level and low impedance. The phase shift of the output with respect to the input is adjustable at the front panel over the full range of 360°.

6.2.3 Converter

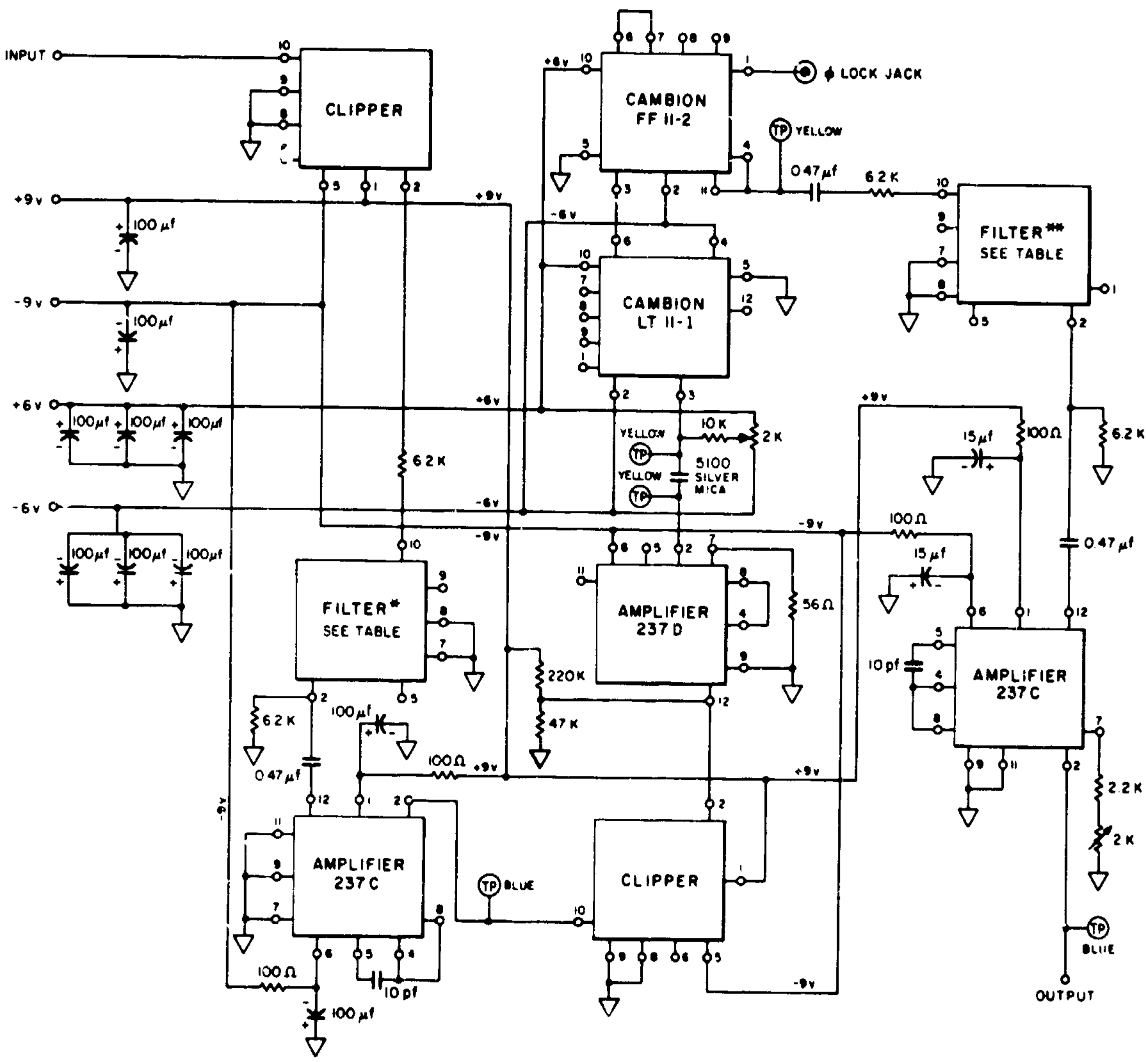
The converter, illustrated in Fig. 13, receives the f_2 signal from a preamplifier. The signal is further clipped, filtered, and amplified to provide an amplitude-stabilized signal. The amplitude-stabilized signal is clipped and the resulting pulse is amplified by a high-frequency pulse amplifier to a level adequate to operate the level trigger LT 11-1,



CHASSIS FREQUENCY	FILTER FREQUENCY*	CAPACITANCE VALUE**
35 KCPS	35 KCPS	2200 pf
23 1/3 KCPS	23 1/3 KCPS	3300 pf
20 KCPS	20 KCPS	3900 pf
16 1/2 KCPS	16 1/2 KCPS	4700 pf
13 1/3 KCPS	13 1/3 KCPS	5600 pf
11 KCPS	11 KCPS	6800 pf

Note † *Mounted on front panel*

FIG. 12 PREAMPLIFIER (SCHEMATIC)



CONVERTER	FILTER*	FILTER**
23 1/3 KC to 35 KC	23 1/3 KC	35 KC
13 1/3 KC to 20 KC	13 1/3 KC	20 KC
11 KC to 16 1/2 KC	11 KC	16 1/2 KC

FIG. 13 CONVERTER (SCHEMATIC)

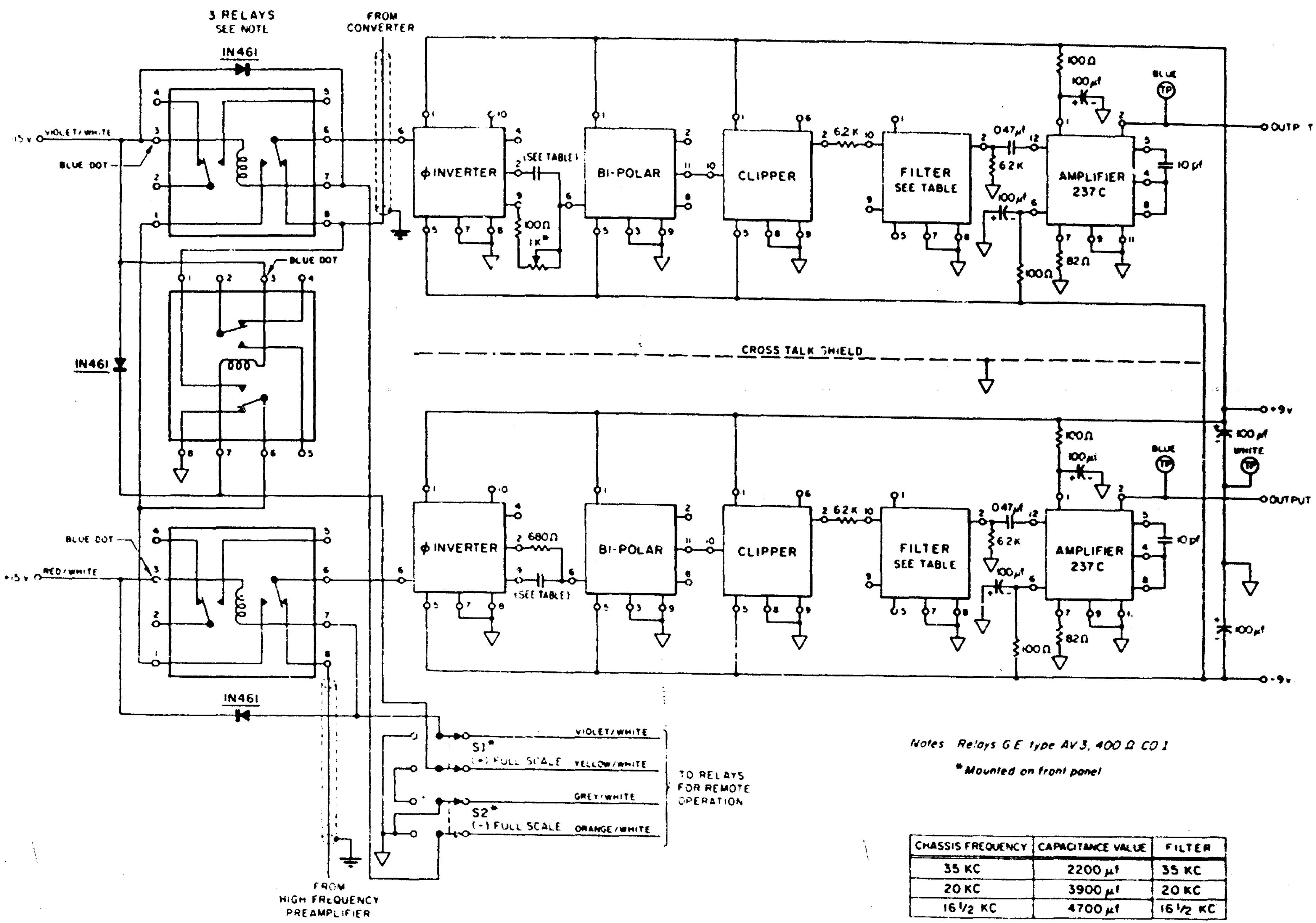
which drives a flipflop. The purpose of the flipflop is to divide the frequency of the signal by two. The phase-lock signal is applied to the flipflop at its reset input. A filter, at the output of the flipflop, is tuned to the third harmonic of the frequency of the flipflop output. Since the flipflop output is one-half the frequency of the input signal, the output of the filter is $3/2f_2 = f_1$. A final amplifier standardizes the level of the signal and provides a low impedance at the output of the converter.

6.2.4 Compensator

The compensator, shown in Fig. 14, has a pair of identical channels. A set of three relays is arranged at the input so that one signal can be applied to one of the channels while the other input is grounded, or the same signal can be supplied to both channels. These configurations provide signals that correspond to full-scale positive, full-scale negative, and zero, respectively. When the relays are not actuated, one signal is applied to each channel - the normal operating mode. Each channel has a phase-shifting network and clipper/filter/amplifier combination to produce an amplitude-stable output. A phase-shift network in one channel is adjustable by a multiturn potentiometer, so that, when the same signal is applied to both channels, the phase of the compensator output will cause the phasometer to indicate a phase shift of zero.

6.2.5 Phasometer

The phasometer, shown in Fig. 15, has a pair of identical input circuits that receives the pair of signals from the compensator. The signals are clipped, passed through a high-frequency amplifier, and further shaped by a pair of level



Notes Relays G E type AV 3, 400 Ω CO I

*Mounted on front panel

CHASSIS FREQUENCY	CAPACITANCE VALUE	FILTER
35 KC	2200 μf	35 KC
20 KC	3900 μf	20 KC
16 1/2 KC	4700 μf	16 1/2 KC

FIG. 14 COMPENSATOR (SCHEMATIC)

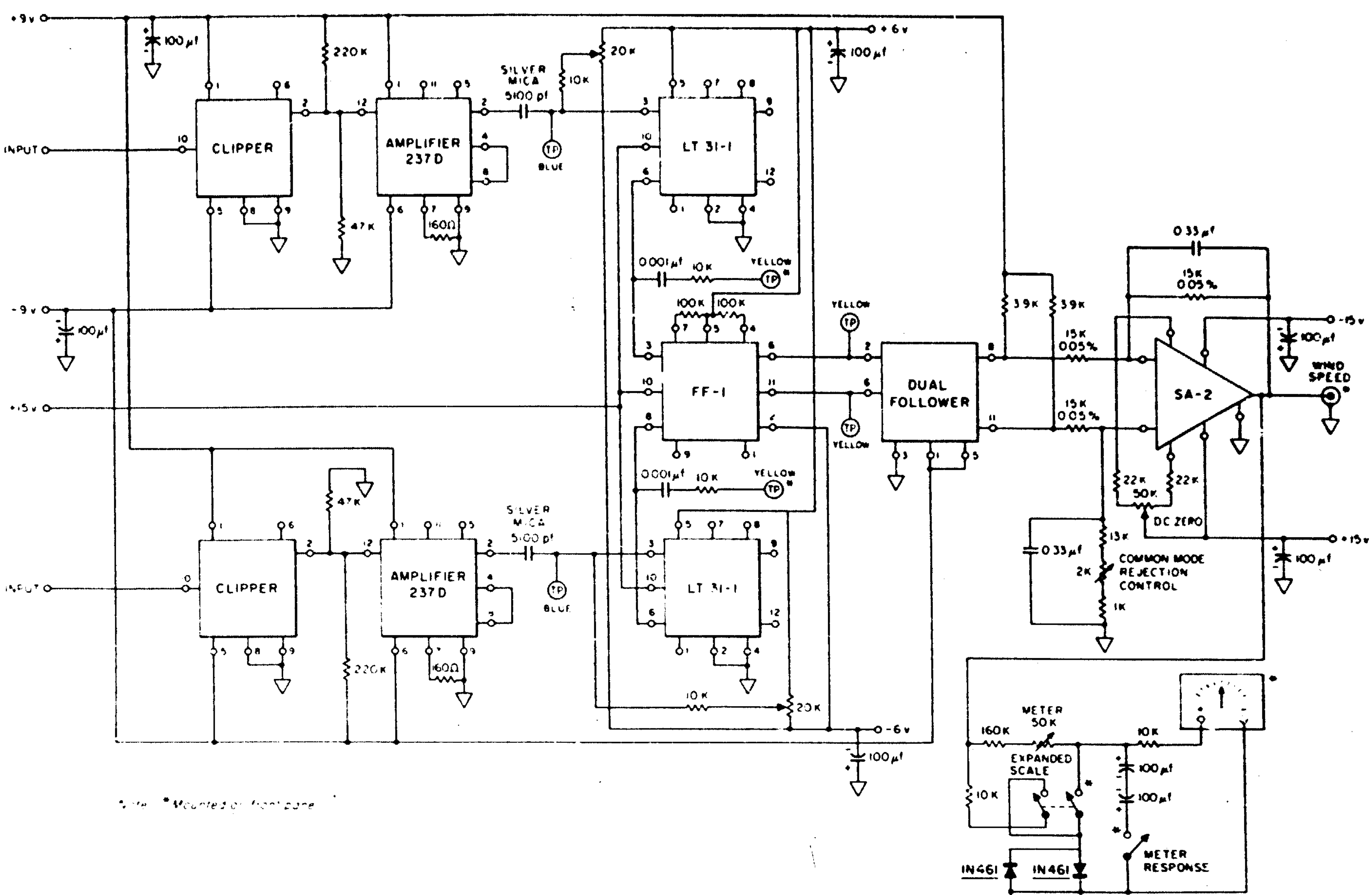
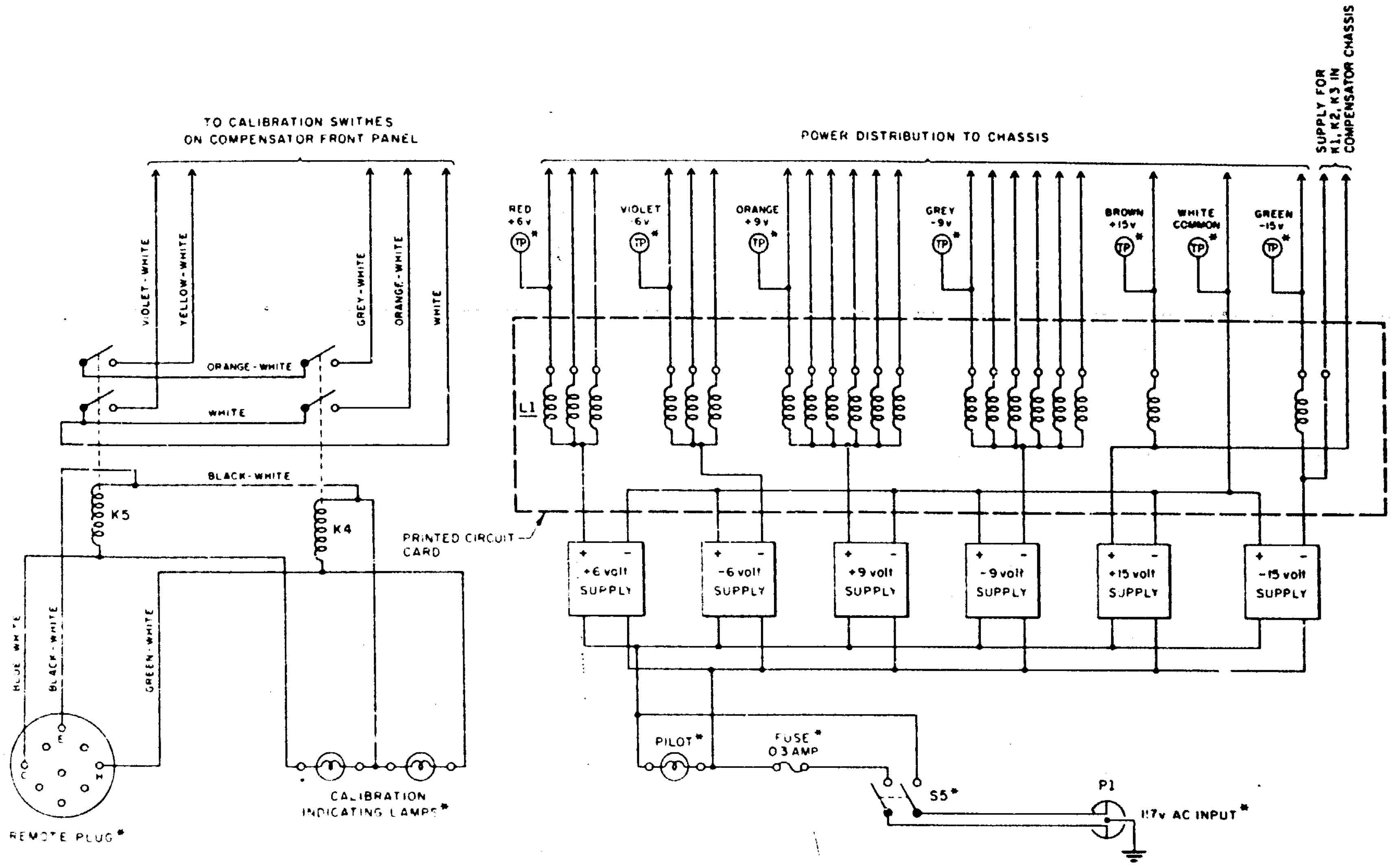


FIG. 15 PHASOMETER (SCHEMATIC)

triggers which operate the complementary inputs of a flipflop. The voltage swing at the flipflop output, (stabilized internally by saturation and cutoff) is supplied through a pair of emitter followers to the inputs of a differential operational amplifier that has a feedback network to provide a low-frequency cutoff of approximately 25 Hz. The output of the operational amplifier is available on the front panel at a coaxial connector. The output also supplies a meter circuit connected to two switches. The *meter-response* switch can introduce shunt capacitance to slow the response of the meter. The *expand-scale* switch increases the sensitivity of the meter so that an expanded scale is available for zero setting of the unit.

6.2.6 Master Panel

The master-panel schematic, Fig. 16, shows several power supplies and networks of decoupling chokes that supply power to the several subassemblies. On the front panel are color-coded test points to measure the various supply voltages.



Notes: All chokes (L1) 400 mh, 135 turns of No 30 wire, on Cambridge Thermion Corp. Ferrite coil form No 2964.

* Mounted on front panel

FIG. 16 MASTER PANEL (SCHEMATIC)

7.0 Operating Procedure

Mount and align the anemometer probe and the anechoic box. The probe should be leveled.

The electronic equipment for each component of the anemometer is housed in an individual case; hence, the operating procedure is identical for all three components. The operating panel for one component is illustrated in Fig. 17.

CONNECT EQUIPMENT...The cables are brought back along the boom and the standpipe inlets are secured at the top of each component box (Fig. 2).

A letter (R or E), a number (1, 2, or 3), and a letter (A or B) are stamped on the gold-plated connectors that terminate the coaxial cables. The first letter designates receiver (R) or emitter (E). The number designates the component of the wind: 1 is the vertical component, 2 is the left horizontal component, and 3 is the right horizontal component. The second letter is used to distinguish between the two frequencies assigned to the channel: the letter A corresponds to the higher frequency and B corresponds to the lower frequency. Connect the coaxial cables to the inputs of the two preamplifiers and to the outputs on the generator according to the cable marking. Connect the unmarked coaxial connector to the wind-speed output. Connect the twist/lock power connector and a remote-control connector (if used) to their respective receptacles on the main chassis.

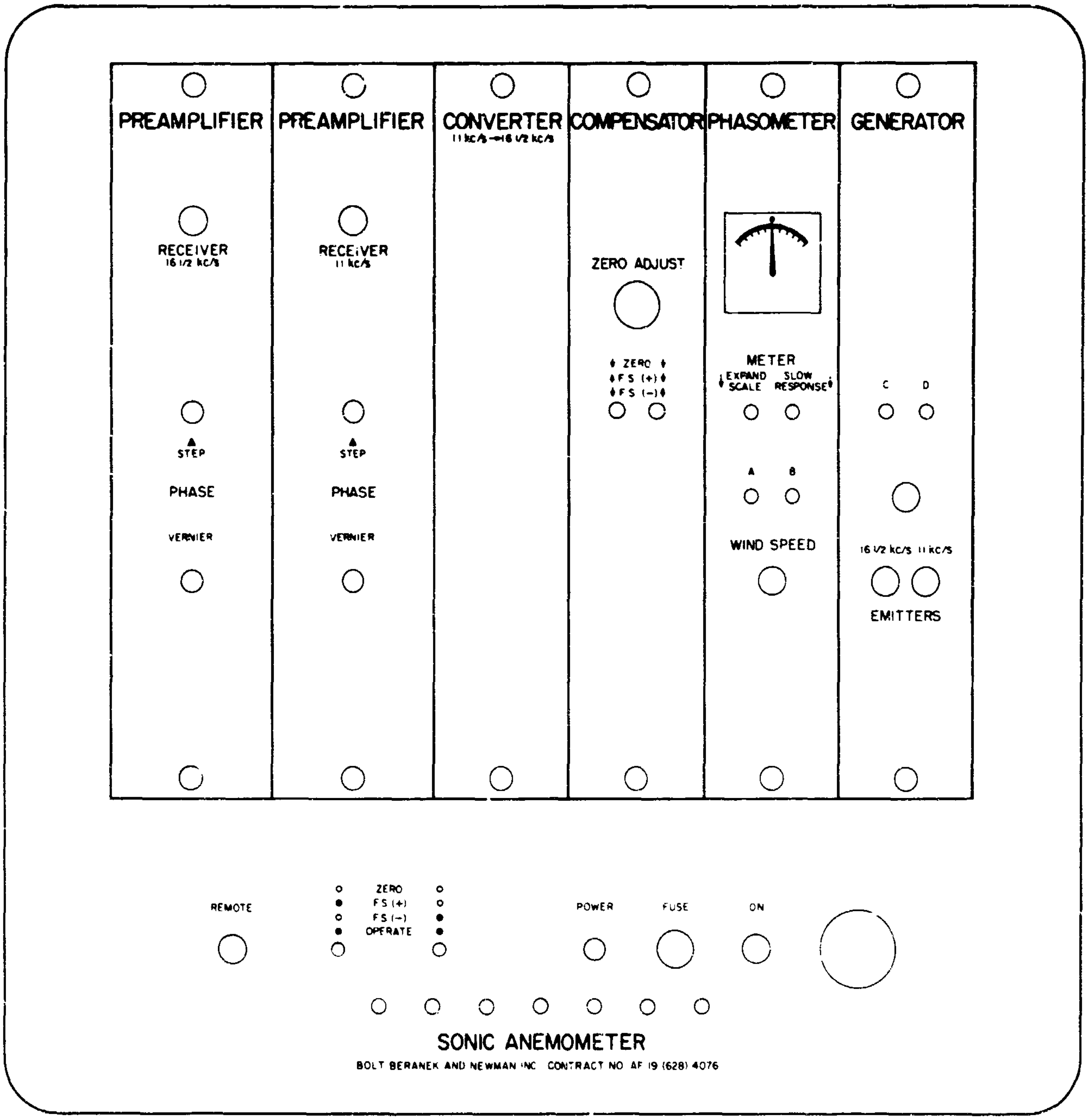


FIG. 17 FRONT PANEL OF ELECTRONICS UNIT FOR ONE COMPONENT OF SONIC ANEMOMETER

TURN ON POWER...Turn on the equipment for each wind component with the switch located next to the power connector. The pilot lamp indicates that power is being supplied to the unit. Although the unit may be operated immediately, a 30-min. warmup period is recommended to bring the equipment to equilibrium at the operating temperature.

SET ZERO POINT...Actuate the two toggle switches on the *compensator* simultaneously. Adjust the recessed potentiometer, *zero adjust*, to obtain a null indication on the *phasometer*. Actuate the *expand-scale* switch on the *phasometer* to make a final, accurate setting of the *zero adjust* (but keep the other two switches depressed).

CHECK FULL-SCALE CALIBRATION...Actuate the toggle switches on the *compensator* one at a time. If the unit is operating properly, the meter on the *phasometer* will indicate on the red lines at full-scale positive and negative. The *wind-speed* output also produces the full-scale output voltages; hence, if a recorder is connected, full-scale calibration marks will be obtained.

PLACE PROBE IN ANECHOIC BOX...To adjust phase lock it is necessary first to place the anemometer probe in the anechoic box. If the anemometer is already mounted on the tower, open the anechoic box and swing the boom in until the mounting hub of the probe sets into the round gasket (Fig. 3). Then close the anechoic box and fasten the clasps.

ADJUST PHASE LOCK...A short length of coaxial cable is supplied with each electronics case. Remove the non-shorting cap from the unmarked coaxial connector on the *generator,* disconnect the cable to the receiving input of the right hand *preamplifier,* and connect the short cable between the two points. Rotate the red knob *step* to align the mark on the knob with that on the chassis; set *vernier* to the calibration that is indicated on the inside cover of the aluminum case, and lock *vernier* in place. Now use *step* and *vernier* on the left hand *preamplifier* to obtain a zero indication on the meter. (The meter-switch *expand scale* can be used to make this setting more precise.) Check the phase-lock setting by rotating *step* on the left hand *preamplifier* an equal number of *steps* clockwise and counterclockwise of the set point. A proper adjustment has been achieved when the meter reads in steps toward full scale and approximately the same number of steps can be obtained in either direction. After checking the adjustment, return *step* on the left hand *preamplifier* to the point for which the meter indicates zero. Lock the *vernier,* remove the short length of coaxial cable, and reconnect the receiver cable.

Note the meter indication. If the unit has not been recently calibrated, the meter will probably no longer indicate zero. If necessary, readjust the red knob and associated *vernier* to obtain a zero indication on the meter. Then rotate red knob *step* clockwise and counterclockwise to check that a reasonable range of uniform steps to $\pm$ full-scale are available. When *step* and *vernier* are properly adjusted for zero meter reading, lock *vernier.* Both *verniers* are now locked and the meter indicates zero.

CHECK THE REMOTE CONTROL...If remote operation of the full-scale and zero checks is desired, the computer cable should now be connected to the jack marked *remote*. Operating the relays remotely will set the two lamps to the right of *remote* in any of the following four configurations: (1) If both lamps are lit, the computer is requesting a zero check. (2) If the right lamp is lit but not the left, the computer is requesting a full-scale positive check. (3) With the left lamp lit but not the right, the computer is requesting a full-scale negative check. (4) With both lamps out, the unit is in operate status.

After similarly adjusting the three channels of the sonic anemometer, open the anechoic box and swing the boom so that the probe is facing the prevailing wind. Before further operation, the probe should be rechecked to ensure that it is level. A small level placed on top of the junction box may be used for this purpose, or an electric level can be made with mercury switches.

If moist weather is expected, the cover may be closed by loosening the thumbscrew on the support bar. If severe weather is expected, the locking clasps should be fastened. The anemometer is ready for use.

NOTE 1: The procedures that we have described above would set the anemometer zero reference were there no reflections in the anechoic box. We have found that the reflections are not negligible; consequently, an offset may be present in the data obtained with the anemometer.

NOTE 2: If any phase-sensitive electronic or acoustic component of the anemometer assembly should change, the zero set will change. Under large temperature changes, the phase of the transducers changes; consequently, frequent rezeroing of the anemometer by repeating the entire above procedure may be necessary during periods when the temperature changes significantly over a period of an hour or so.

8.0 Acknowledgments

A substantial contribution to the work described in this report was made by Dr. Francis M. Wiener before his untimely death. Several persons have contributed in the development of the anemometer: notably, J. Colaruotolo, J. A. Melaragni, and H. E. Tamulonis.

9.0 References

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APPENDIX A

CIRCUIT DIAGRAMS

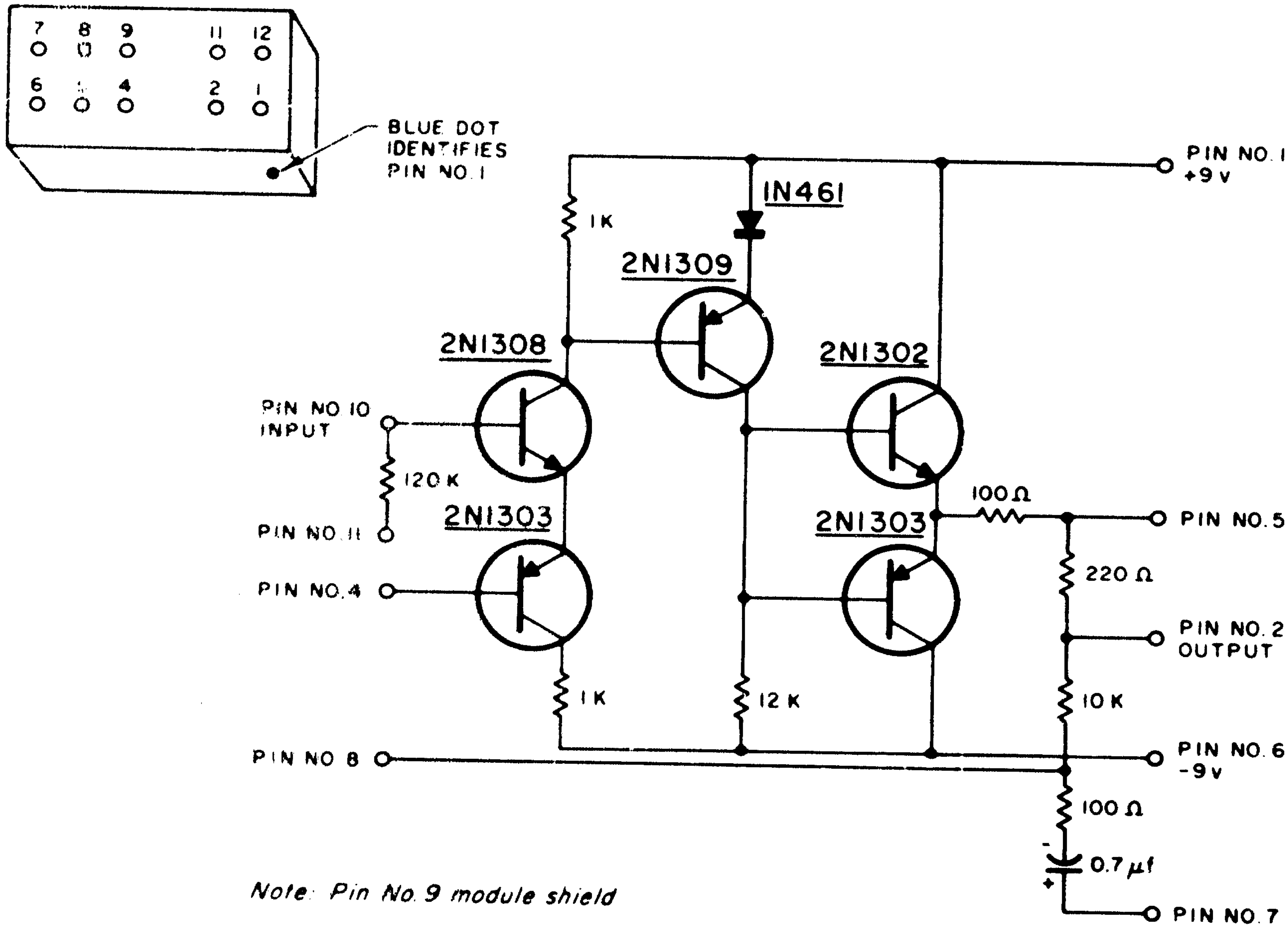
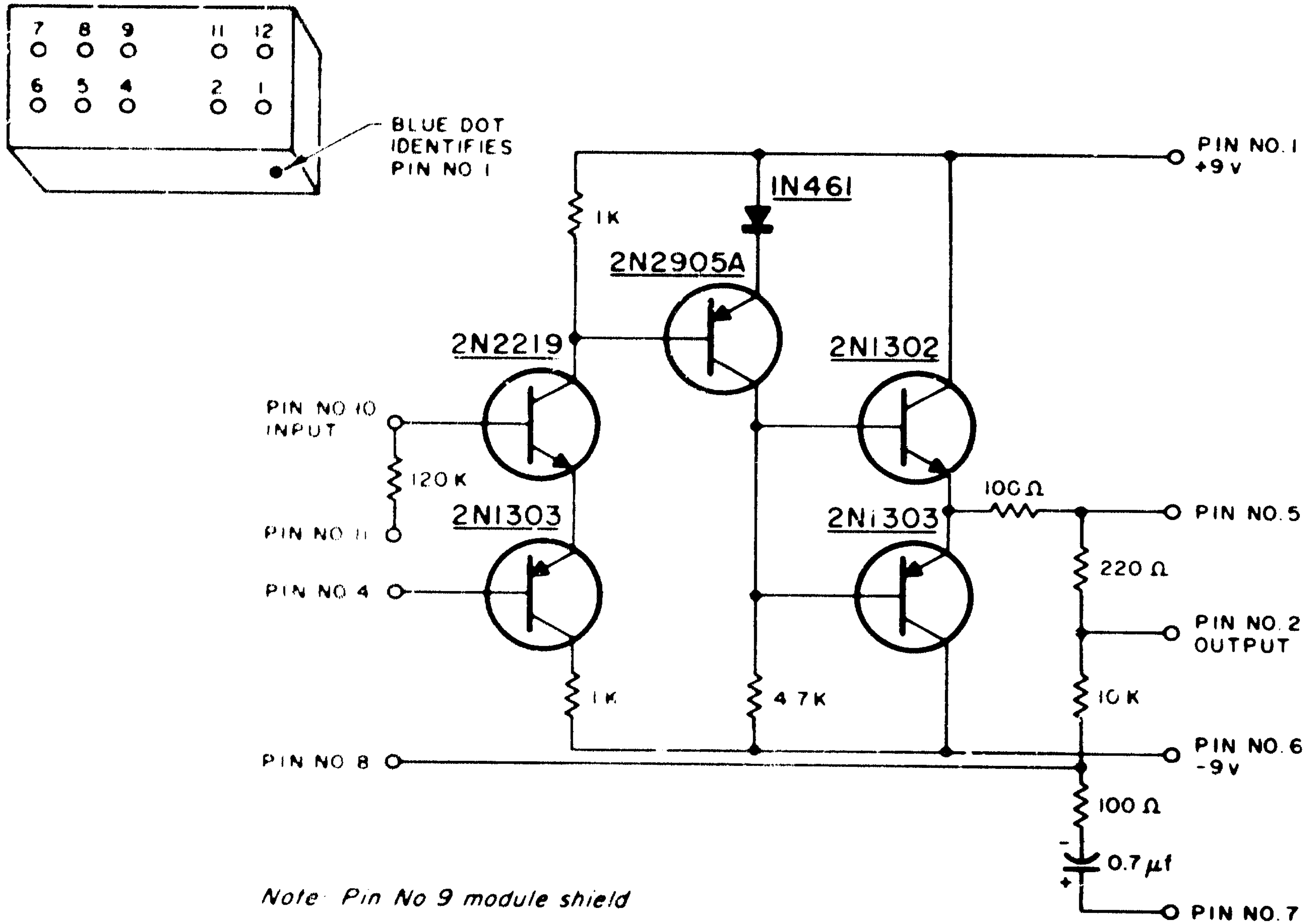
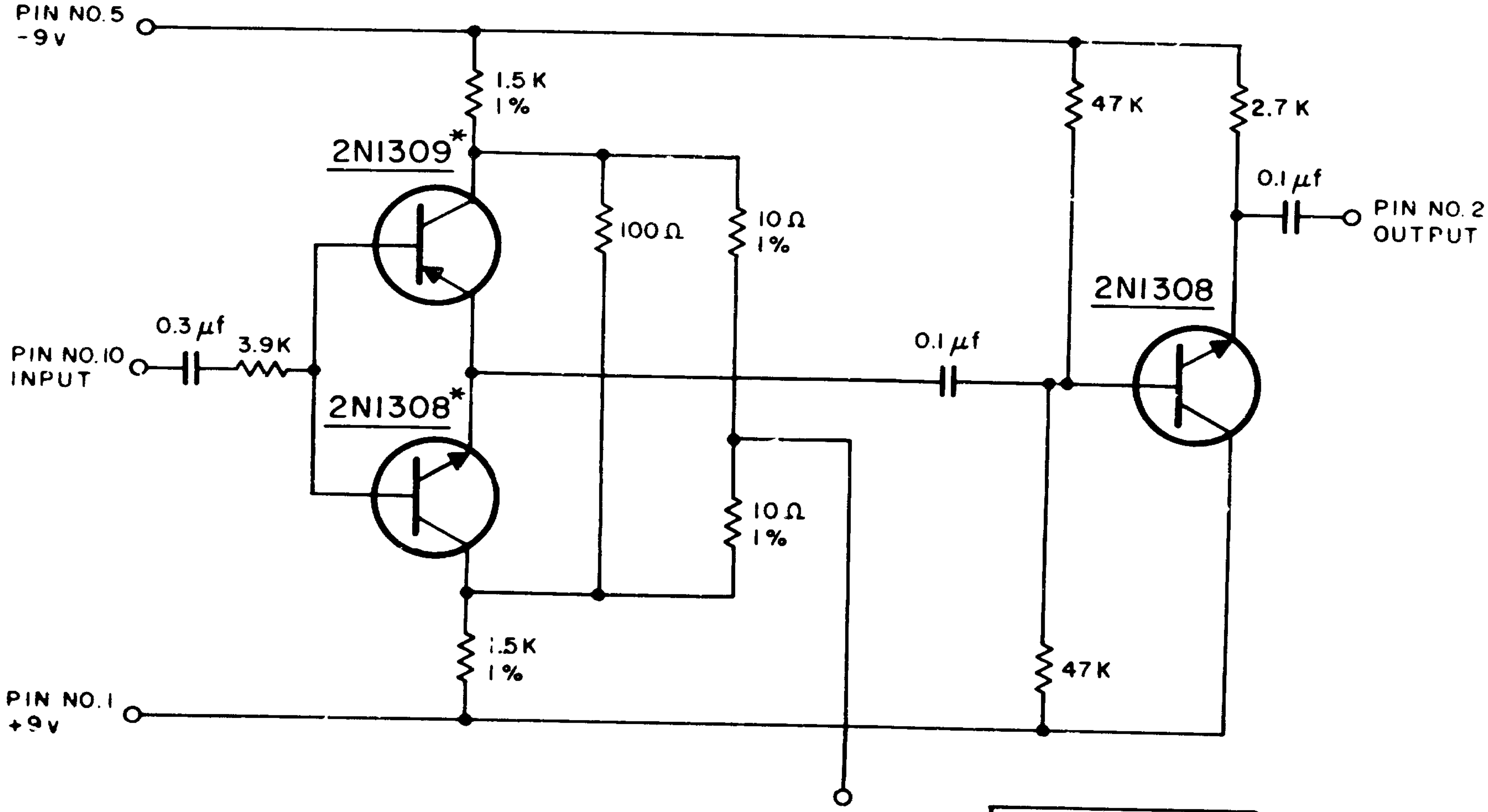


FIG. A-1 AMPLIFIER 237C



Note Pin No 9 module shield

FIG. A-2 AMPLIFIER 237D



Notes: *Pin No 6 no connection*
Pin No. 8 module shield

**Selected for minimum phase shift for -20 db change in input level from the nominal 1 volt*

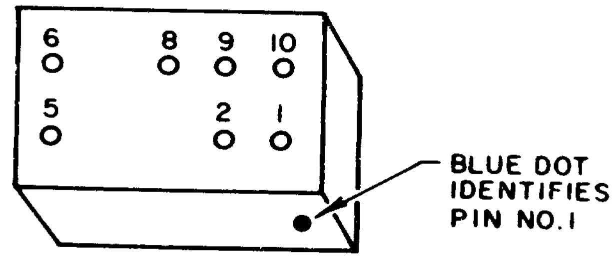
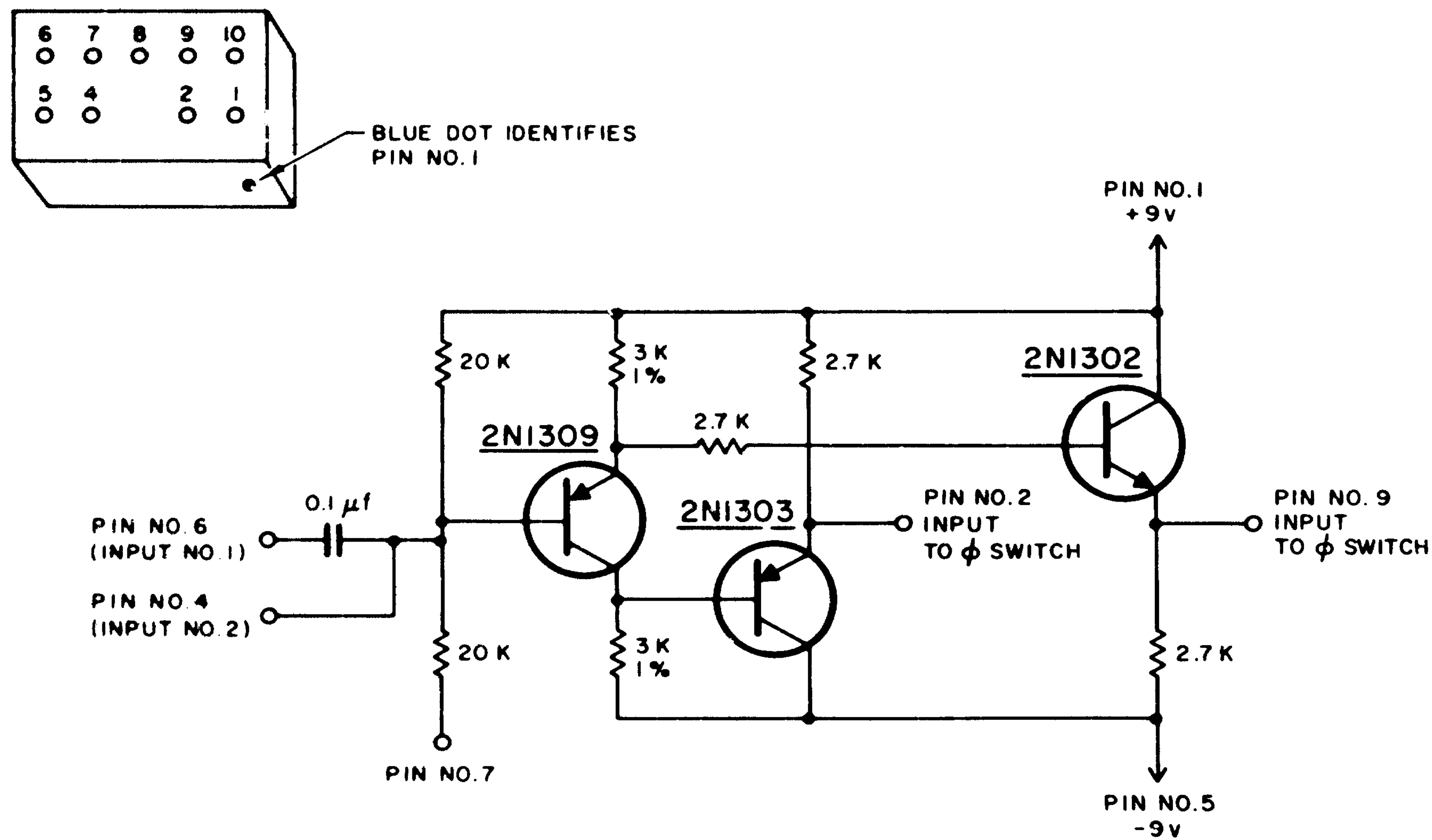
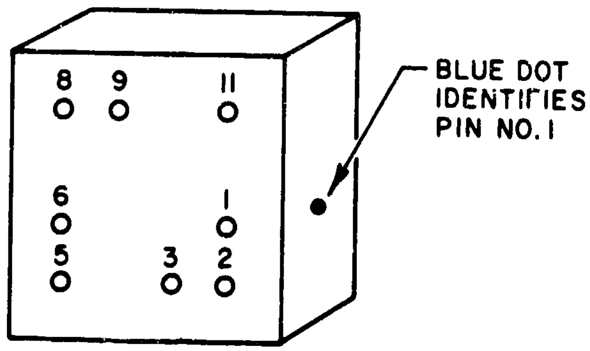


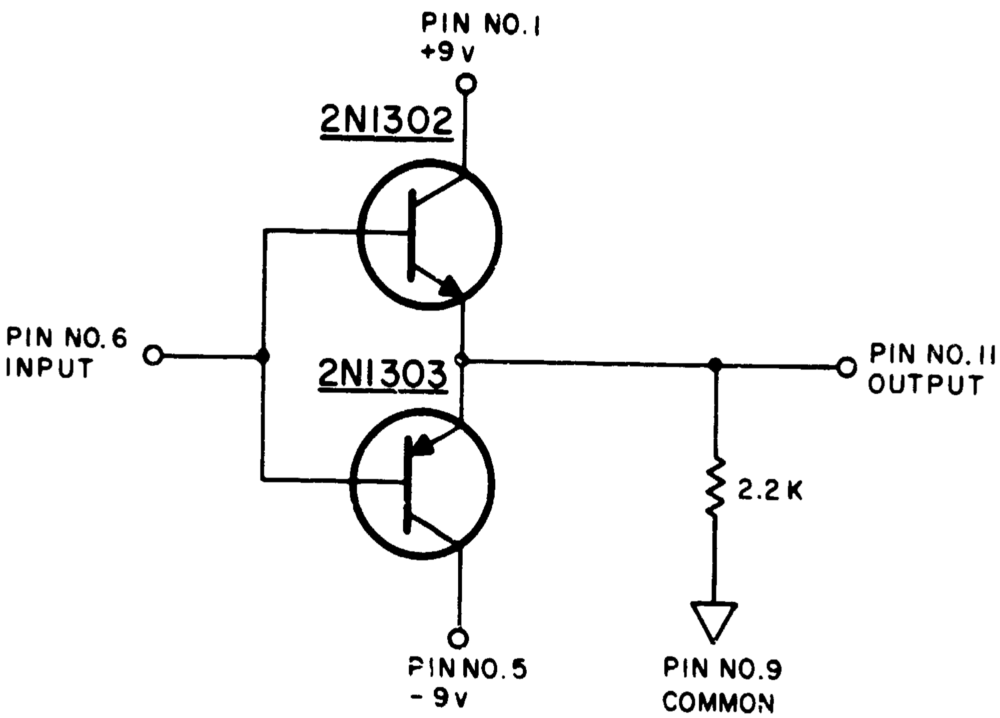
FIG. A-3 CLIPPER



Note: Pin No. 8 module shield

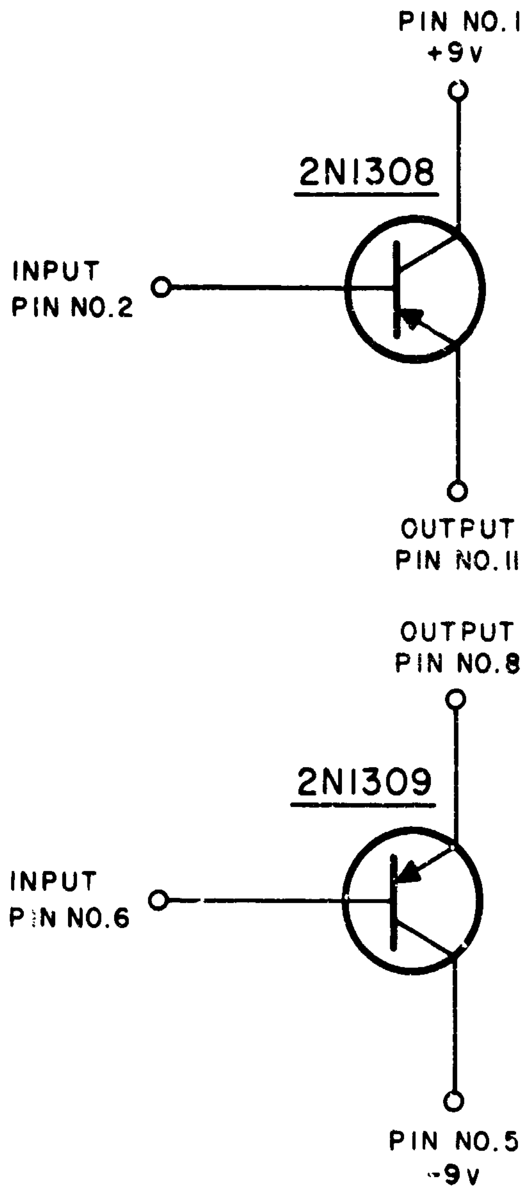
FIG. A-4 Φ INVERTER





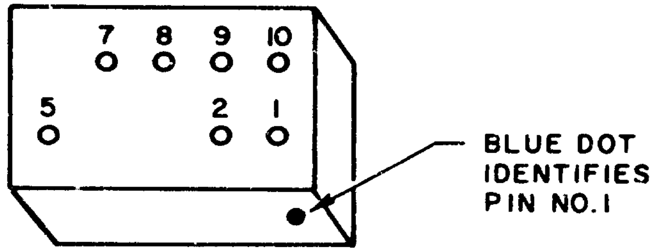
Note: Pin No. 3 module shield
Pin No. 2 no connection
Pin No. 8 no connection

FIG. A-5 BI-POLAR



Note: Pin No. 3 module shield

FIG. A-6 DUAL FOLLOWER

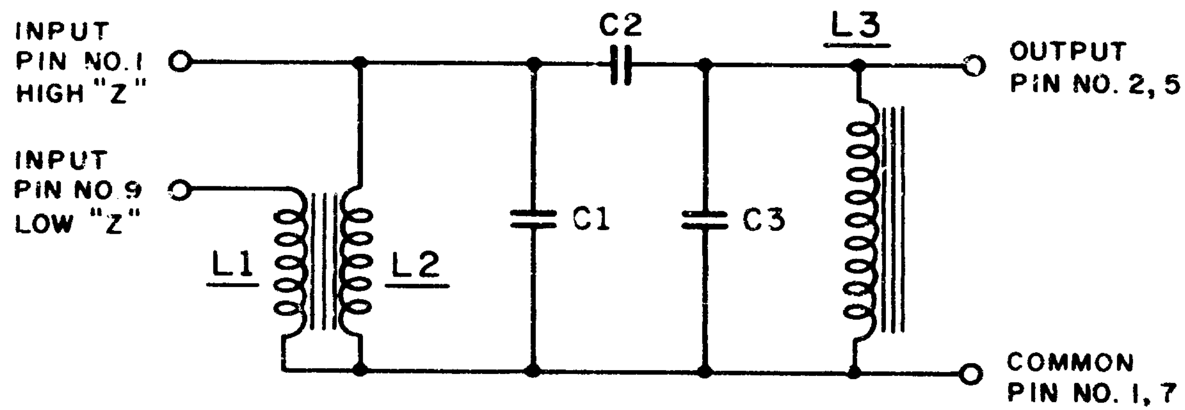


Notes: Pin No. 8 module shield

C1, C3 Wesco Type 32 P, 5 % Polystyrene Capacitor

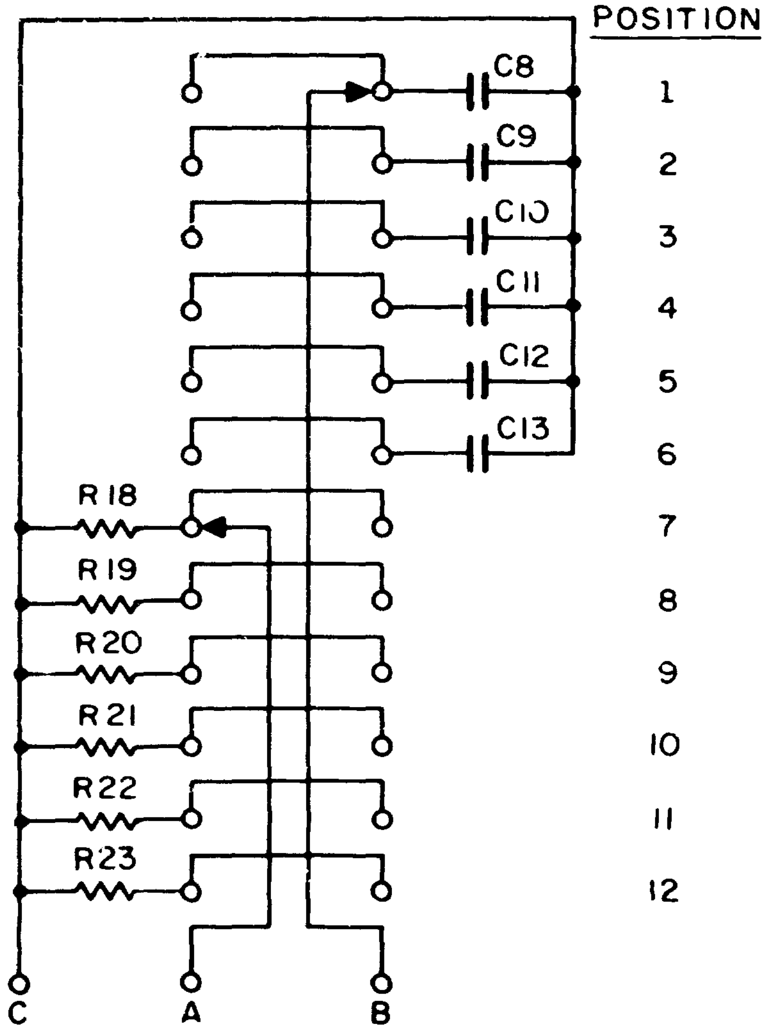
C3 Elmenco Silver Mica

L1, L2, and L3 wound as Toroid Torvid 55050-D4 Magnetics Inc



FREQUENCY (KC)	L1 (NO. OF TURNS)	L2, L3 (NO. OF TURNS)	C1, C3 (MICROFARADS)	C2 (PICOFARADS)
35	48	150	0.02	1000
23 1/3	59	185	0.033	1500
20	60	190	0.033	1800
16 1/2	67	210	0.047	2200
13 1/3	70	220	0.05	2700
11 KC	78	246	0.06	3300

FIG. A-7 FILTER

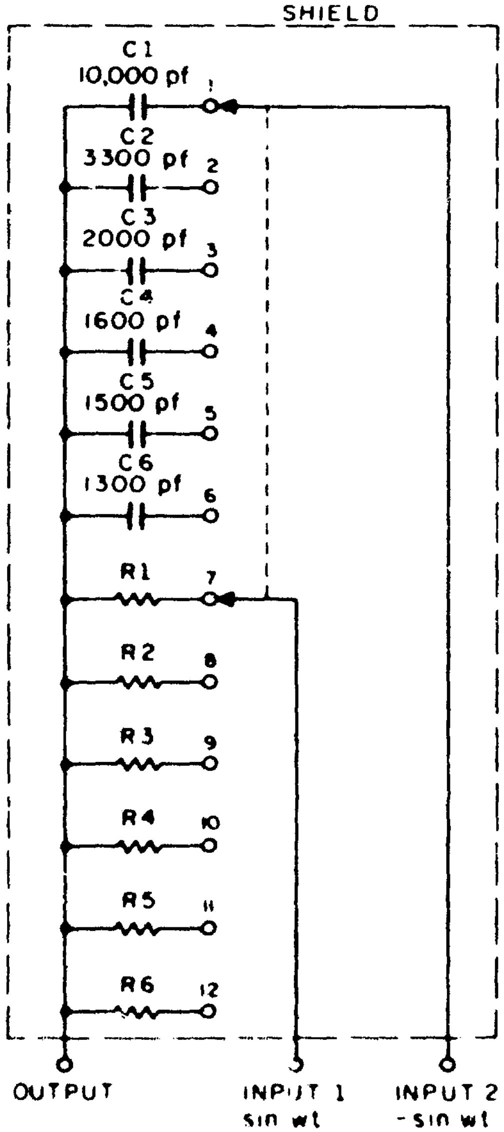


*C8 17,500 pf, 1%, 500 v
*C9 6000 pf, 1%, 500 v
*C10 3680 pf, 1%, 500 v
*C11 2870 pf, 1%, 500 v
*C12 2420 pf, 1%, 500 v
*C13 2240 pf, 1%, 500 v

*R18 1975 Ω, 1%, 1/2 watt
*R19 1850 Ω, 1%, 1/2 watt
*R20 1590 Ω, 1%, 1/2 watt
*R21 1220 Ω, 1%, 1/2 watt
*R22 765 Ω, 1%, 1/2 watt
*R23 266 Ω, 1%, 1/2 watt

*SELECTED FROM 5% STOCK

FIG. A-8 TYPICAL PHASE SWITCH



Notes: Capacitors are Elmenco silvered mica DM-20 5%

Resistors were selected to give a phase shift increment of 30° ±5°

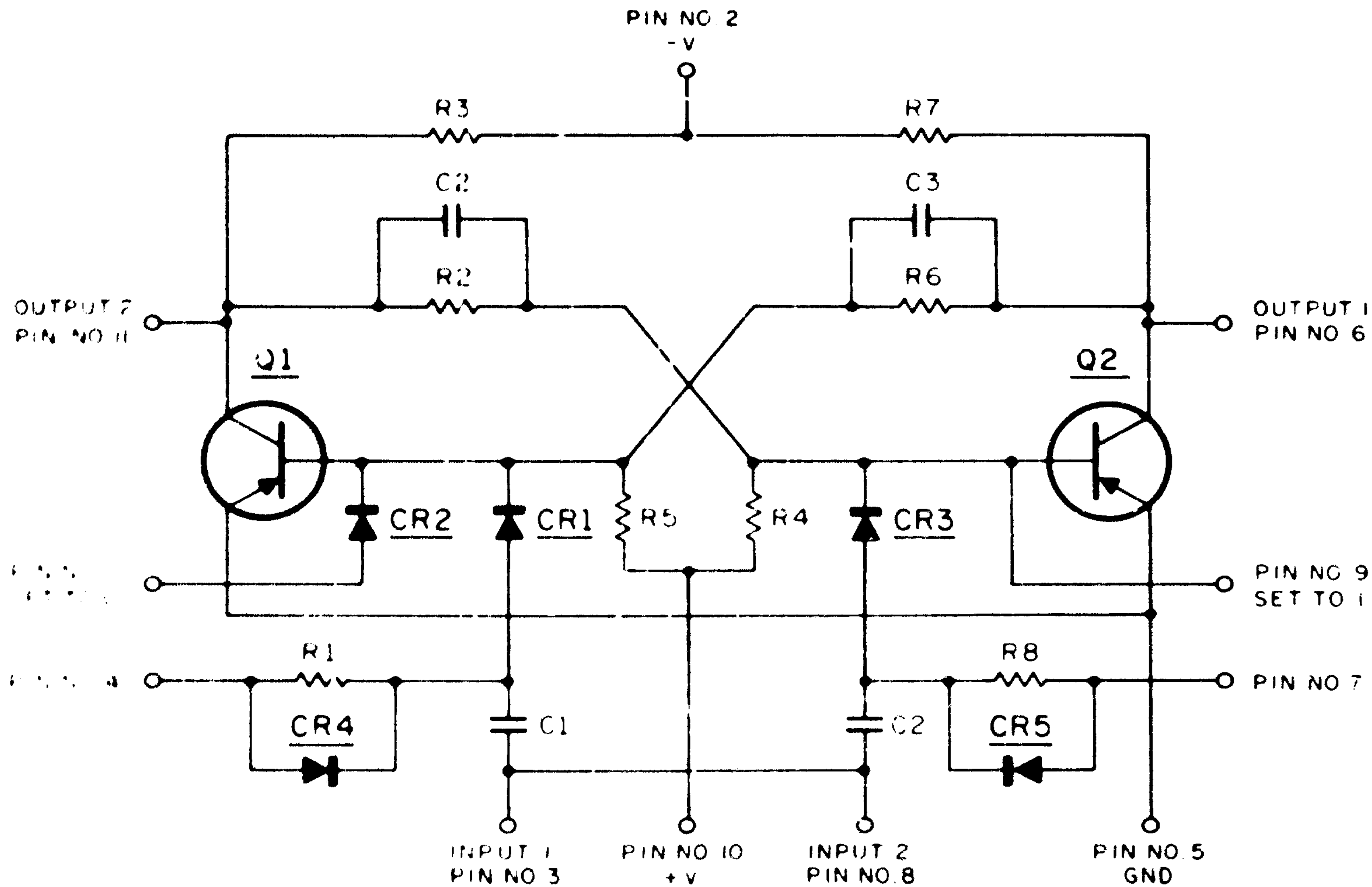
Nominal values of resistors are given in table

Shield - Zero Mfg. Co.
ZR26 1 15/16" long
ZR27CF 5/16" long

12 position continuous rotation switch OAK Mfg Co. No. 399217-A with two 12 position non shorting wafers

FREQUENCY	35 KC	23 1/3 KC	20 KC	16 1/2 KC	13 1/3 KC	11 KC
R1	3.6 K	5.1 K	6.2 K	8.2 K	10 K	13 K
R2	3.3 K	4.7 K	5.6 K	7.5 K	9.1 K	10 K
R3	2.7 K	4.3 K	5.1 K	6.2 K	8.2 K	9.1 K
R4	2.2 K	3.3 K	3.6 K	4.3 K	5.6 K	6.8 K
R5	1.3 K	1.8 K	2.4 K	2.7 K	3.3 K	4.3 K
R6	470 Ω	680 Ω	750 Ω	750 Ω	1.0 K	1.5 K

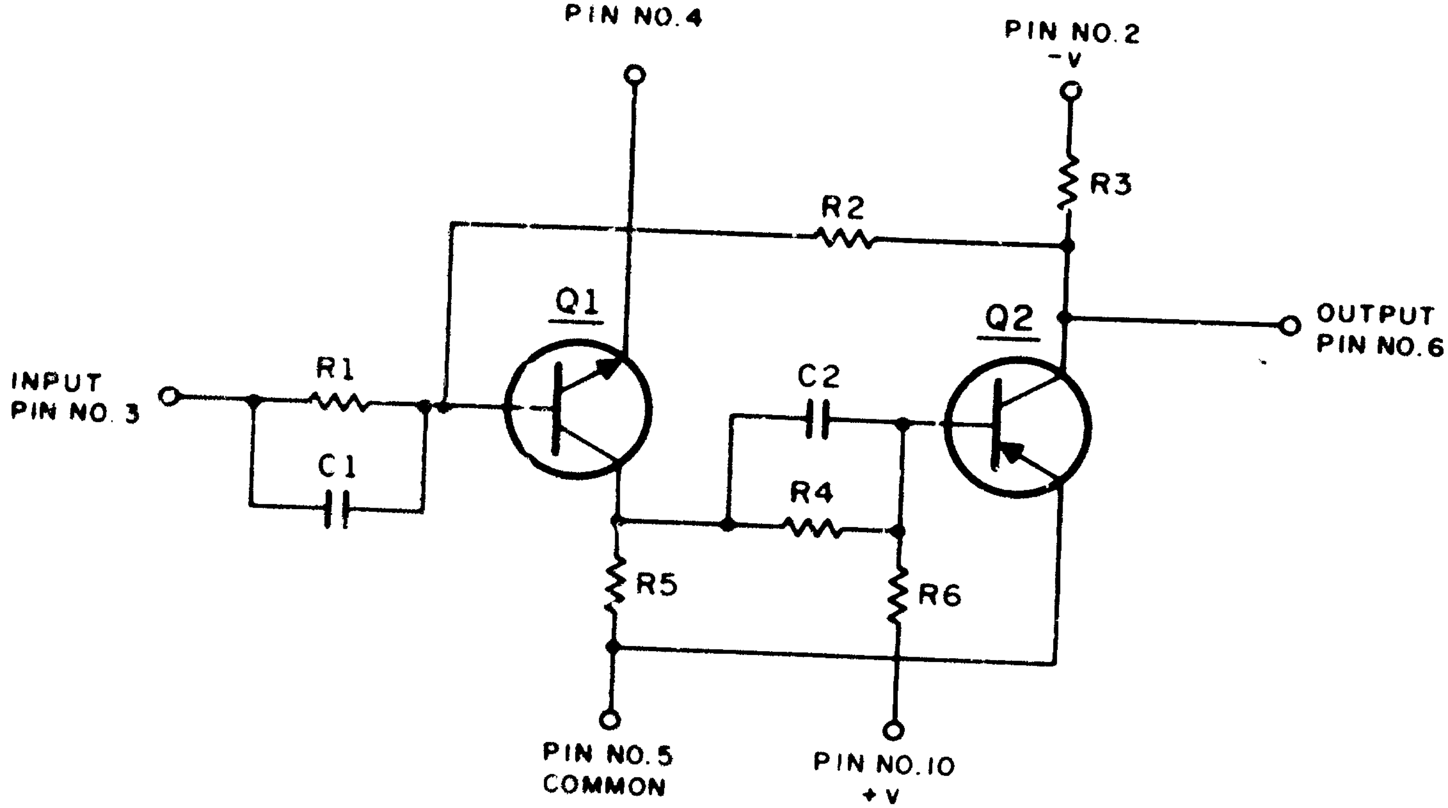
FIG. A-9 30° STEP PHASE SHIFTER



Note This circuit is of a proprietary nature, therefore the values for components are not given

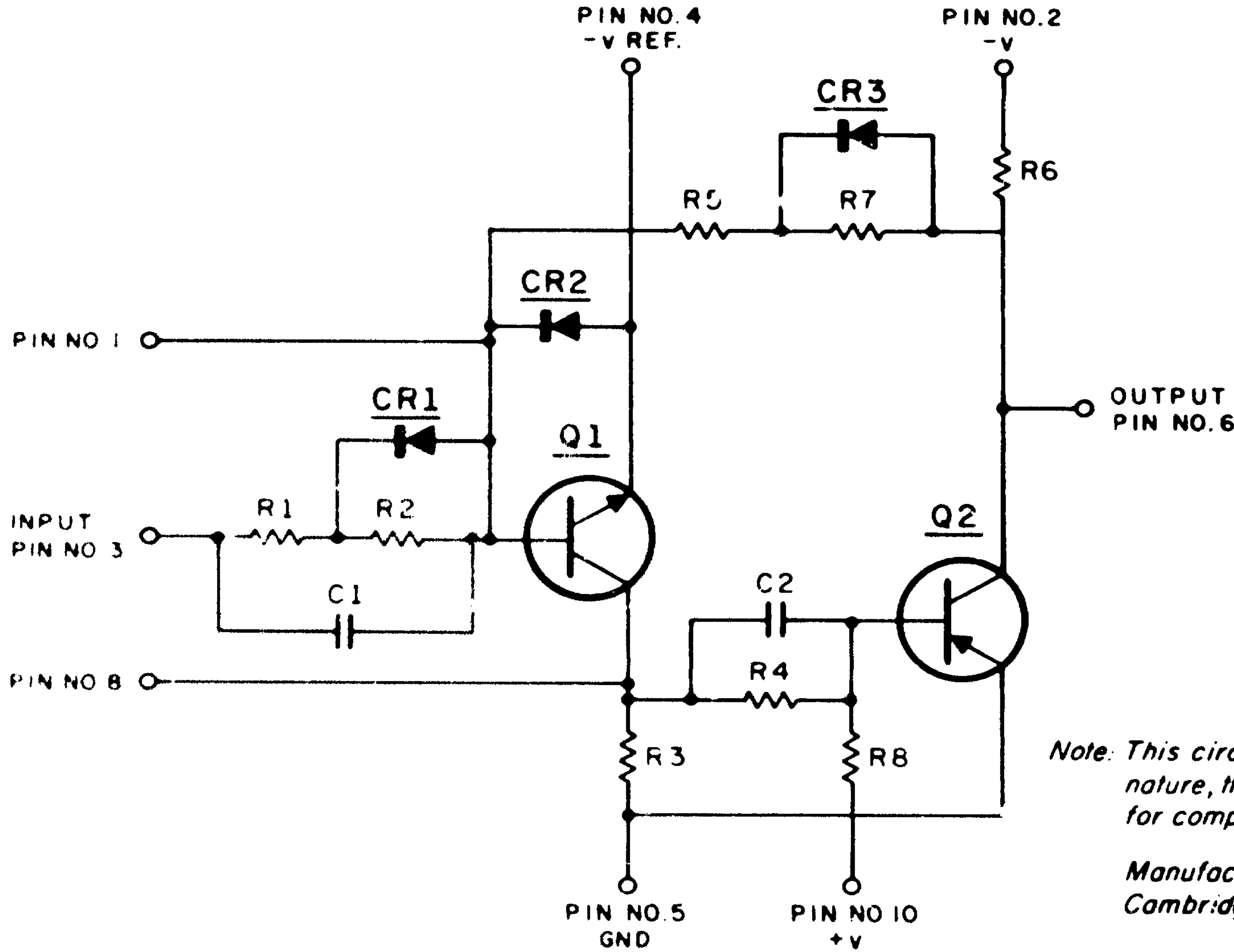
Manufactured by Cambridge Thermionic Corp

FIG. A-10 CAMBION FF-11-2



Note: This circuit is of a proprietary nature, therefore the values for components are not given

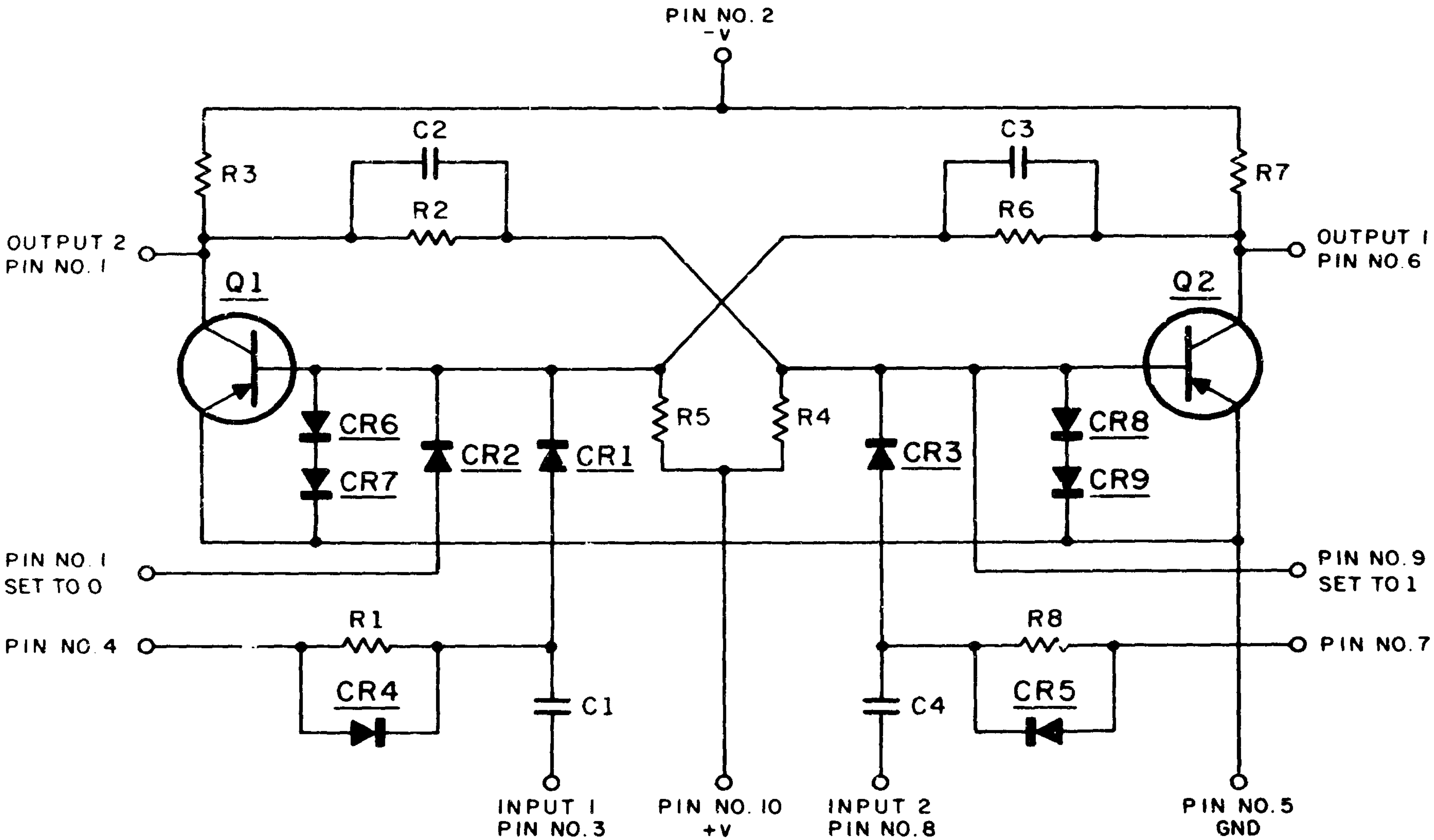
FIG. A-11 CAMBION LT-11-1



Note: This circuit is of a proprietary nature, therefore the values for components are not given

Manufactured by Cambridge Thermionic Corp

FIG. A-12 LEVEL TRIGGER MODULE (LT-31-1)



Note: This circuit is of a proprietary nature, therefore the values for components are not given

Manufactured by Cambridge Thermionic Corp.

FIG. A-13 FLIP-FLOP MODULE FF-2

APPENDIX B

MODIFICATIONS OF THE SONIC ANEMOMETER

The anemometer described in the body of this report has been modified. The modifications were introduced to correct operational shortcomings of the anemometer, which were uncovered during field tests conducted as part of Project Windy Acres in August 1965. The field tests indicated that the zero reference of the anemometer shifted with diurnal variations of temperature. We determined that the source of this temperature-dependent drift was the change in resonant frequency of the transducers. A change in the resonant frequency of a transducer produces a change in the phase shift between the electrical and acoustical signals associated with the transducer. Because the sonic anemometer obtains wind velocity by measuring wind-induced phase shift, any change of relative phase is indistinguishable from a shift in the wind velocity.

To reduce the temperature sensitivity of the transducer, we redesigned the units with the following objectives: (1) to reduce directly the temperature sensitivity of the frequency-determining element and (2) to make the transducer tunable so that the drift in phase characteristics of each set of transducers would be compensatory.

Another result of the field tests was the recognition that the range of mean winds and fluctuations was such that the horizontal-component of the anemometer was not often driven to full scale. Hence, the modification program included an increase in the pathlength of the horizontal axes of the anemometer to reduce the full-scale range of the horizontal axes.

The transducers were replaced by units of a new design. The diameter of the transducers was reduced from 5/8 in. to approximately 1/2 in. The sensitive element is, as before, a piezoceramic disk cemented to a circular plate. A long cylindrical shell and end plate are machined as one piece. The cylinder slides over an expandable arbor. The transducer is tuned, over a limited range, by changing the effective length of the cylindrical shell (i.e., by adjusting the depth of penetration of the solid arbor). A special nickel steel alloy was chosen as the transducer material to compensate the temperature characteristics of the piezoceramic disk. The increase in the length of the transducer required use of a Teflon mounting (and neoprene in some cases).

Figure B-1 is a photograph of the modified sonic-anemometer probe. Note, by comparing Fig. B-1 with Fig. 4(a), the new transducers, their mounting, and the increased horizontal pathlengths. Unnecessary structural material has been removed from around the transducers—hence, the modified probe has a more-open aspect—this tends to reduce the turbulence created by the probe in the region through which the acoustic signals propagate.

The change in the pathlength changes the nominal range of wind speeds for each axis. Figure B-2 shows a modified version of the block diagram shown in Fig. 11. Note that the horizontal axes are changed to 15 cm and that the nominal ranges are now ±10 m/sec.

The meter scales on the phasometer are changed to conform to the new range. A toggle switch was installed to replace the short cable that had been used in the initial aligning procedure of the anemometer (see Sec. 7.0 - *Adjust Phase Lock*).

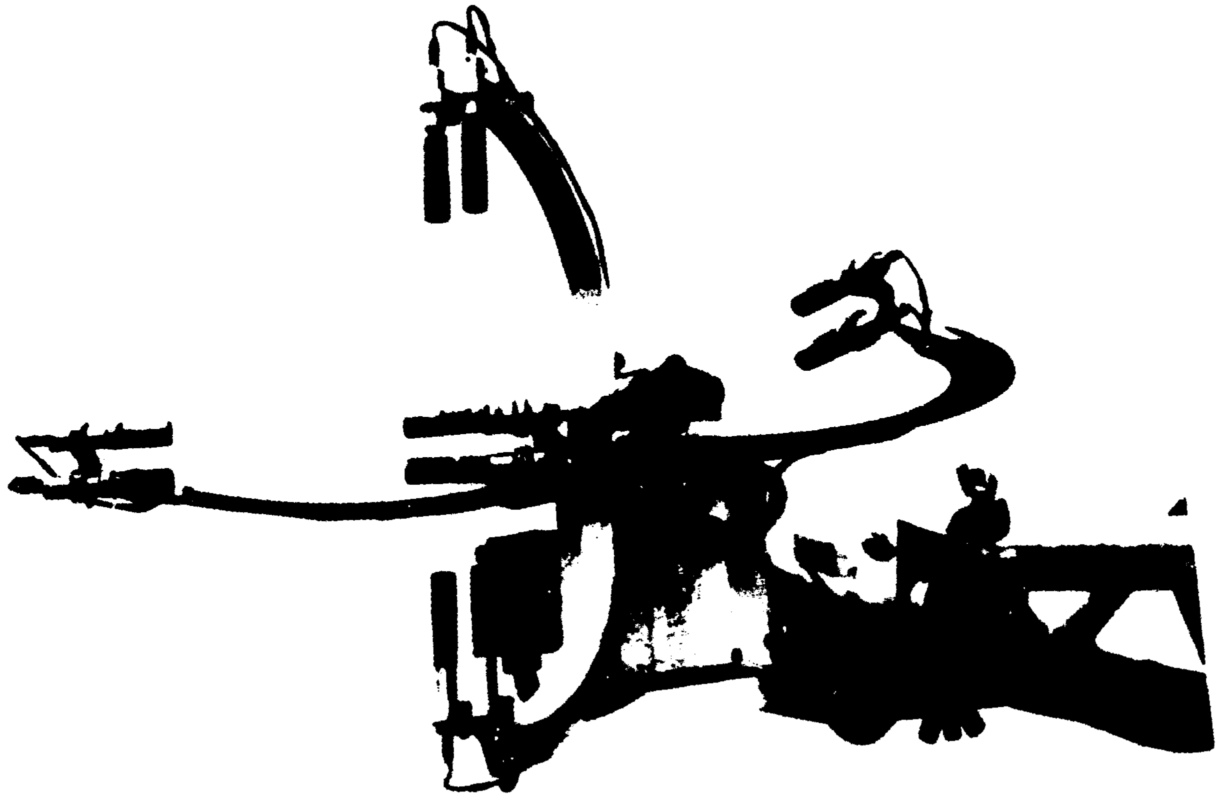
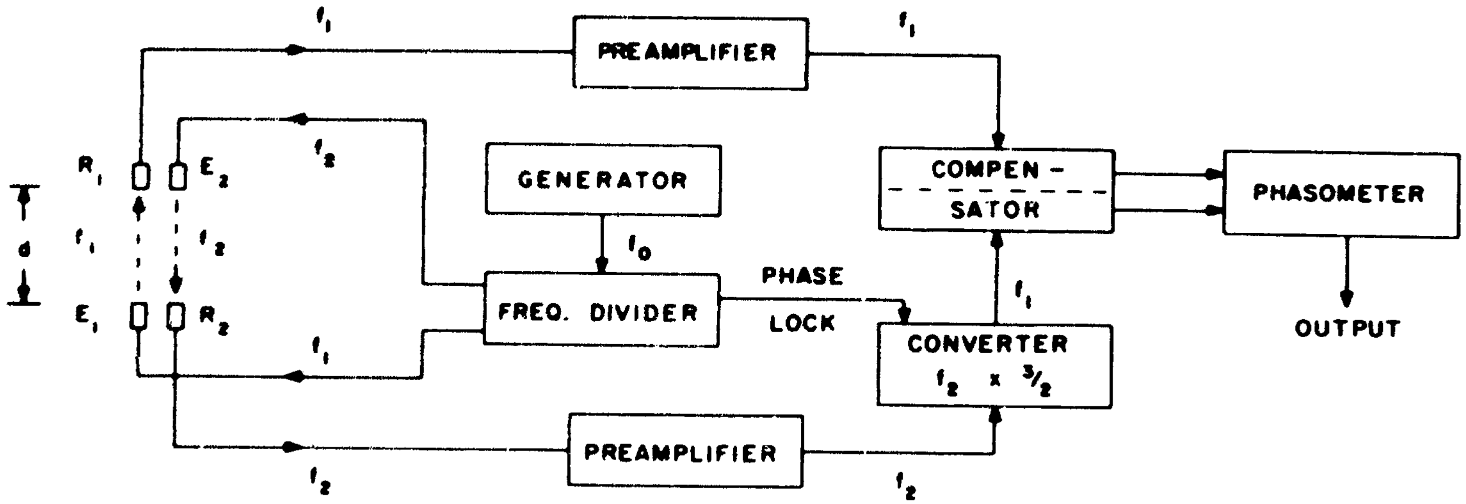


FIG. B-1 MODIFIED SONIC-ANEMOMETER PROBE



NOTE: E_1 AND R_1 TUNED TO FREQUENCY f_1
E_2 AND R_2 TUNED TO FREQUENCY f_2

COMPONENT	f_0	f_1	f_2	d	NOM. RANGE
V_1	80 Hz	20 Hz	$13\frac{1}{3}$ Hz	15 CM	± 10 M/SEC
V_2	66 Hz	$16\frac{1}{2}$ Hz	11 Hz	15 CM	± 12 M/SEC
W	70 Hz	35 Hz	$23\frac{1}{3}$ Hz	20 CM	±4.3 M/SEC

FIG. B-2 BLOCK DIAGRAM OF MODIFIED ONE-COMPONENT SONIC ANEMOMETER

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13. ABSTRACT

A Continuous-Wave Three-Component Sonic Anemometer is described. The anemometer was developed for the Boundary Layer Branch of the Air Force Cambridge Research Laboratories by Bolt Beranek and Newman Inc. (BBN).

A physical description is presented, with several illustrations showing the construction of the anemometer and the manner in which it is mounted.

Design specifications are presented, and the operating procedure is described.

The theory of operation is discussed from the point of view of establishing performance limits on the anemometer.

The overall system is discussed and a detailed description of circuits is presented.

Instructions for operating the anemometer are presented.

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Sonic anemometer						
Measurement of Atmospheric Turbulence						

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